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Final Technical Report

PLANNING SYSTEMS FOR AUTONOMOUS LEGGED VEHICLES

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ERIM Staff Report
MAY 1989

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This report describes efforts to integrate the areas of mobility research and autonomous navigation in support of the Adaptive Suspension Vehicle program. Experimental research on the locomotion of Nubian goats is summarized. A decision model of terrain navigation based upon the experimental results is reported. The Computer Simulation of Animal Navigation, which implements the decision model, is presented. The need for increased flexibility in planning systems is discussed, and a sliding vehicle simulation which incorporates some of the desired features (the Blackboard Planning System) is described. A paper discussing the fundamental notions of search and exploration in autonomous navigation is included.

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PREFACE

The work described in this report represents our effort to integrate the areas of mobility research and autonomous navigation in support of the Adaptive Suspension Vehicle (ASV). This undertaking was made possible through Subcontract with the University of Wisconsin. The University of Wisconsin mission to provide research on autonomous land traversing capabilities for the ASV has been supported by the Defense Advanced Research Projects Agency (DARPA Order No. ARPA-5575) through contract with the Department of the Army (Contract No. DAAE07-86-C-R013). We gratefully acknowledge the support and encouragement of Dr. William Isler of DARPA and Dr. Fernando Alverado of the University of Wisconsin in pursuing this research. The findings and conclusions presented in this report do not necessarily represent the views of the above agencies.

Several members of the group, under the direction of Dr. Robert F. Franklin, were essential to the work described here. Lisa Leon carried out the experimental research with Nubian goats upon which the decision model of navigation was based. Francis Quek was responsible for the CSAN simulation, with assistance from Kristina Van Voorhis and Dr. Laurel Harmon. The Blackboard Planning System represents the combined efforts of Alice Clarke, Nancy Finzel, Dr. Laurel Harmon, Richard Lotero and Kristina Van Voorhis. The computer simulation of search and exploration behaviors presented in Appendix A was developed by Alice Clarke and Kristina Van Voorhis.

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1.0
INTRODUCTION

The robotics research community is striving to endow a wide variety of vehicles with the capability of autonomous mobility. Related research is being undertaken in two intrinsically different test vehicles. The ASV (Adaptive Suspension Vehicle), which uses legs as a means of propulsion, is being utilized to address problems of mobility. Mobility research is concerned with the problem of traveling over terrains of high spatial complexity. Machine autonomy can be defined as the ability of a machine to perform tasks in an arbitrarily complex and dynamic environment without external assistance during operation. Autonomy is a subject of research in the wheeled ALV (Autonomous Land Vehicle) program. By endowing the ASV with a decision system for autonomous navigation over rough terrain, both efforts can be concentrated in one test-bed. In support of the University of Wisconsin's research to provide the ASV with an autonomous land traversing capability, ERIM has undertaken a corollary effort to develop concepts for machine mobility which can be implemented in that project.

The goal of the research program described in this report is to further the understanding of autonomous performance on rough terrain through the investigation of the following areas:

- How does a legged animal select a foothold from among a suite of potential footholds? What sources of information, both internal to the animal (system) and sensed from the environment, are relevant to this problem?
- How does a system (natural or machine) blaze a trail through rough terrain? What constitutes a necessary and sufficient affordance in the environment to be considered a trail and what information is retained by the system to make future use of the trail?
- Given that aspects of a trail are learned, how are they used to renegotiate a trail when the system is facing it for the second (or Nth) time?

Several specific tasks were undertaken for the purpose of investigating the above questions through animal experiments and computer simulation:

- Performing experiments with Nubian goats, maintained at ERIM facilities, to determine their strategies for foothold selection.
- Development of a decision model of legged traversal of unfamiliar terrain, derived from the animal experiments.
- Building of a computer simulation based upon the above decision model, using existing computer facilities.
- Development of a terrain module to simulate a complex and dynamic environment with both tactile and visual properties.
- Development of a graphics display module to provide views of the simulated terrain and a vehicle.

In the report which follows, the animal experiments are discussed briefly (Section 2). This work has been described in greater detail in a report previously submitted to the sponsor. In Section 3, the Computer Simulation of Animal Navigation (CSAN) is presented. The CSAN simulation was later re-cast into a blackboard architecture, the Blackboard Planning System, as discussed in Section 4. Related software developed under this program is described in Section 5.

2.0
FOOTHOLD SELECTION IN A NATURAL SYSTEM

Previous work performed by ERIM in support of the ASV[1] involved studying the locomotion of Nubian goats, as a model species, in confined, experimental situations. These studies showed that analysis of kinematics alone was not sufficient to account for the ways in which quadrupeds use their limbs for crossing rough terrain. The research indicated that the emphasis in experiments needed to be placed on the logical level of control as opposed to simply examining the gaits employed by animals. The resulting preliminary model of information processing mechanisms used by goats in solving terrain problems [1] served as a basis for experiments specifically designed to address foothold selection strategies in Nubian goats.

An experimental protocol was established for exploring the means by which Nubian goats determine the physical characteristics of individual footholds. Results of these experiments were seen to be crucial for understanding movements made and forces applied by a system while evaluating the viability of particular segments of terrain. The basic experimental terrain structure used in our studies of goat locomotion was a runway composed of wooden blocks. The blocks could be arranged into a variety of configurations, for instance a long, narrow path or a cattle guard pattern (Figure 1). Though the configuration of the terrain was changeable, each block was stationary during experimentation. Goat traversal of the terrain was videotaped for subsequent computer analysis.

A variant of this terrain structure was created for the purpose of investigating the role of terrain compliance in the selection of footholds. A prototype, spring-loaded "soft" block was constructed and tested. This new type of block was visually identical to the other stationary terrain blocks but would compress when a force was applied to its surface. Compliance characteristics were added to the terrain by building several "soft" blocks,

[1]This research was performed under DARPA Contract No. DAAE01-84-K-R001 through subcontract with Ohio State University (Contract No. RF452622).

Figure 1. Cattle Guard Configuration of Experimental Rough Terrain Runway

according to the design of the prototype. These compliant blocks were placed into one of the basic rough terrain patterns, specifically a long narrow path configuration.

Since the compliant blocks were indistinguishable from the stationary blocks when viewed from above, the animals could not predict the degree of compliance visually. They were forced to test each foothold individually, using tactile measures to determine its support characteristics. Preliminary results showed that unacceptable footholds based on compliance characteristics were avoided by the goats on subsequent runs across the terrain. It is therefore proposed that the goats memorize the locations of the unsuitable terrain blocks. In addition, distinct changes were seen in the gaits used by goats before and after encountering the compliant terrain. Results obtained from these experiments were integrated into a computer simulation decision system for selecting footholds.

A final report on experiments with Nubian goats conducted under this contract was delivered to the sponsor in the form of a videotape, as per prior discussions with the sponsor.

3.0
A COMPUTER SIMULATION OF ANIMAL NAVIGATION

The behavioral studies with domestic goats and research on a theory of autonomous mobility for robotic vehicles[2] led to a decision model of legged traversal of unfamiliar terrain [1]. A Computer Simulation of Animal Navigation (CSAN) was built to explore the implications of the model. The simulation includes both strategic and reactive planning components [2]. It has also been structured to accept synthetic terrain data and real geographic data taken from aircraft and satellites. CSAN examines the sources of information and the decision-making necessary to produce successful terrain traversal [3]. The basic decision model and simulation are presented in this section. The CSAN simulation is discussed further in Appendix A, "AI Simulation of Search and Exploration Behaviors."

3.1 The CSAN Model

Modeling of the decision-making for traversal was done with information at two basic levels. The first concerned *trafficability* -- finding footholds within the immediate vicinity in order to advance (local path planning). The second concerned the *utility* or cost to the animal of terrain to be traversed (global route planning) [4].

In the model, traversability requires both vision and touch. Vision is used in two ways: for detecting the presence of potential footholds within the reach of a given leg and then for examining the surface properties of each potential site to assess its suitability. Selected, candidate footholds, ordered in the desired direction of travel, are then tested by simulating the application of force by a leg. Figure 2 illustrates this model of sensing and perception for foothold selection. As a simple analogy, imagine crossing from one side of a shallow stream to another by finding stones to step on. First, stones must be found which lead across the stream. Then the surfaces of the stones must be examined to see whether

[2]Research supported by DARPA through subcontract to Martin Marietta (Contract No. GH4-116861).

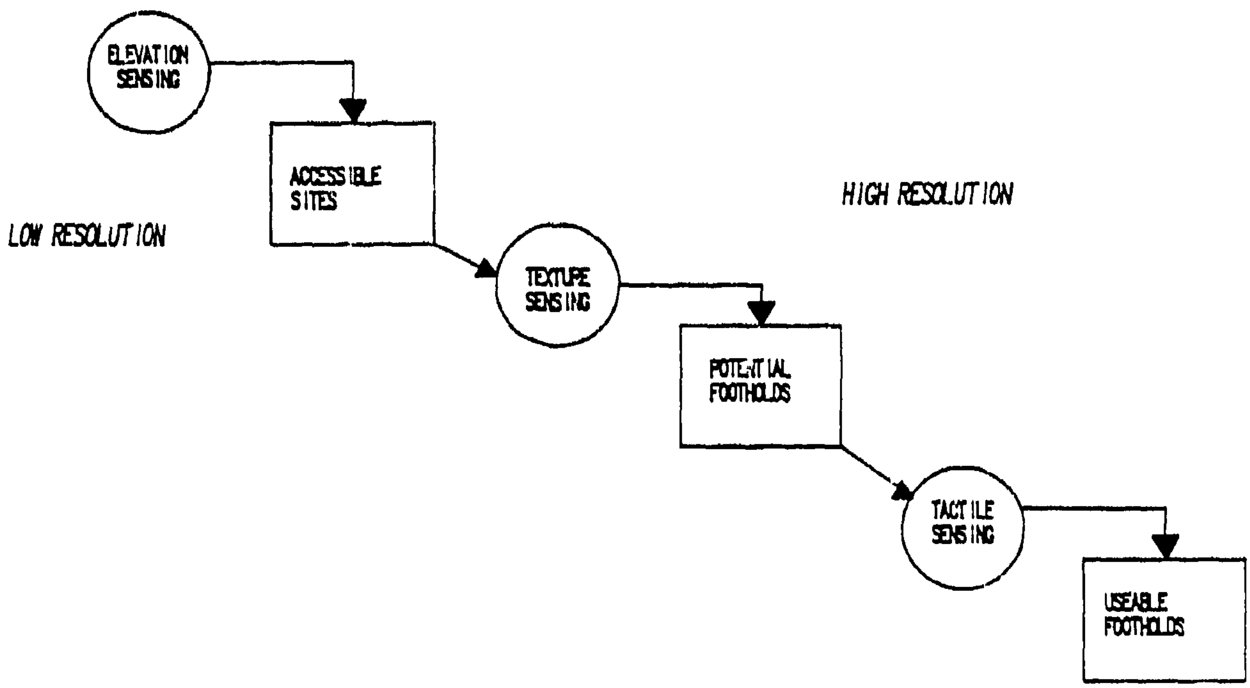


Figure 2.

Sensing and Perception for Foothold Selection

or not they are too slippery to step on. Finally, the stability of each stone in the stream bed must be established by testing with a foot. This basic sequence of actions is repeated time and again by ungulates as they cross unfamiliar ground, resulting in a path or trail.

Prior terrain knowledge is provided in the model by a global "cost" map and a method of finding the shortest course between two points on the map, called a route. Both cost and utility are incorporated into the global map. Numerical values are assigned such that low values represent the most desirable terrain with high values being least favorable. This scale parallels the intuitive notion of "cost" and the map is therefore typically referred to as a "cost" map. The global decision level is referred to as the "utility level." The cost and utility assessment of terrain is based on the following: 1) memory of the terrain, represented as a map; 2) memory of the utility of the terrain elements, including an assessment of their traversability and relative safety; 3) a means for assessing the costs of traversal relative to the current motivational state of the animal, e.g., why the particular movement is being entertained. Considering motivation allows for a different interpretation of the same terrain when foraging and when attempting to escape a predator.

Together, the terrain trafficability and utility elements form the decision model illustrated in Figure 3. Route considerations, based on cost or utility determine where the decision-system will attempt to locate footholds. Within that region, the trafficability portion of the system uses the three-level perception model shown in Figure 2 to locate footholds.

3.2 The CSAN Simulation

The two-level decision model of Figure 3 was implemented in the CSAN simulation. Because the primary purpose of the simulation was to examine the logical level of control in rough terrain navigation, only the forelegs of a legged vehicle were modelled. Experiments had indicated that the Nubian goats often employed a "follow-the-leader" gait, in which the same foothold is used first by the forefoot and then by the hind foot. The sensing and perception model of Figure 2 was incorporated through simulation of low and high resolution vision as well as tactile sensing.

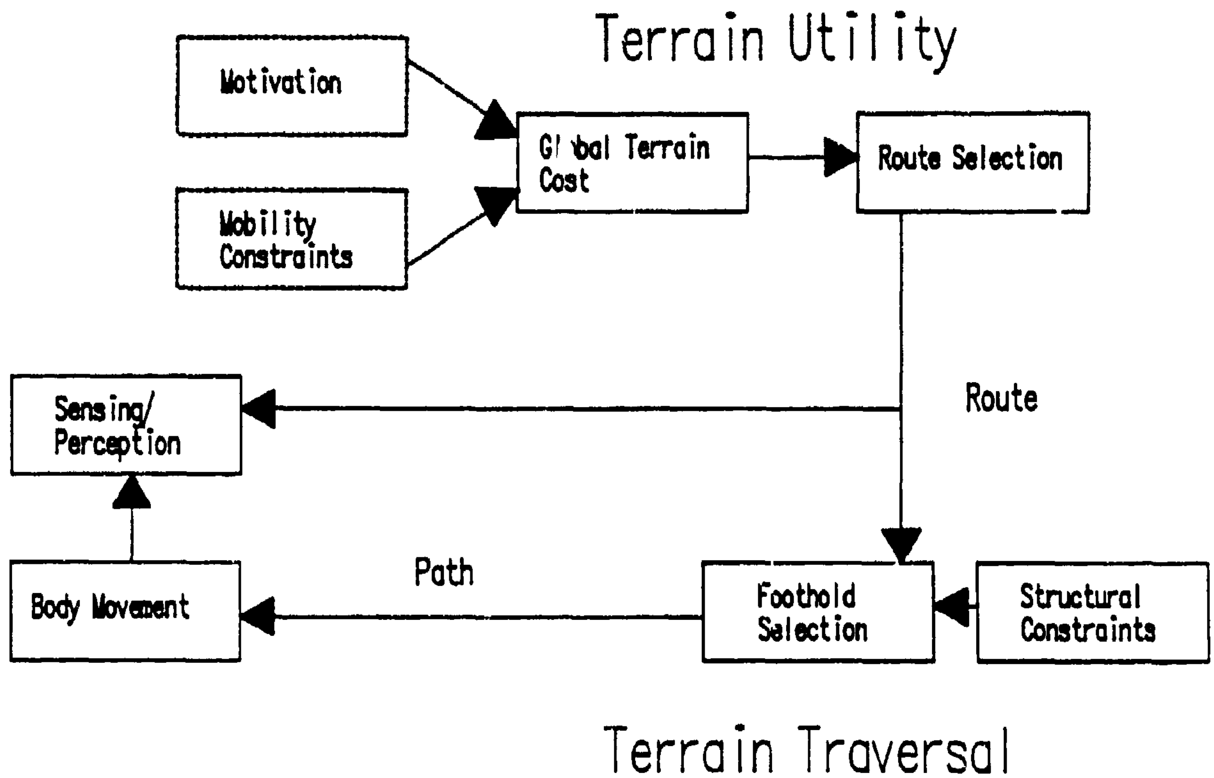


Figure 3.

A Decision Model of Terrain Traversal

The overall model for the simulation included two decision subsystems. The utility subsystem generated routes to be taken to a goal considering: 1) the motivation for movement, 2) the overall mobility capabilities of the animal (including physiological and anatomical constraints), 3) any available prior knowledge of the terrain. For a given route, the traversal decision subsystem attempted to find footholds as close to the route as, 1) the structural constraints of the body permitted (length of legs, ability to jump, ...etc.) and 2) the location of footholds allowed. Suitable footholds were located using the sensing/perception model described in the text and illustrated in Figure 2.

The first version of the CSAN simulation was built in Zetalisp on a single Symbolics 3670 computer. Object-oriented programming was used throughout the simulation, facilitating the development of map-handling functions and permitting the construction of an extensive graphics display in a reasonable length of time. As discussed below (Section 4.0) the simulation was later expanded, re-written in Common Lisp, and distributed over two Symbolics machines.

Representation of the simulation "world" at both utility and trafficability levels consisted of Cartesian-based maps, 512 x 512 arrays whose elements correspond to either the cost or elevation at a particular location. Elevation maps were obtained either through fractal terrain generation methods (see Section 5.1, below) or from a digital terrain database.[3,4] The utility or cost world representation is prepared by passing the elevation map through cost functions prior to a simulation run. The result is a map containing utility or cost of traversal information which is spatially registered with the elevation. At the start of a simulation run, the utility decision sub-system of the model is given a version of the cost map which contains only one-ninth of the original information, derived by a down-sampling technique. This is the only *a priori* information available to the planning system.

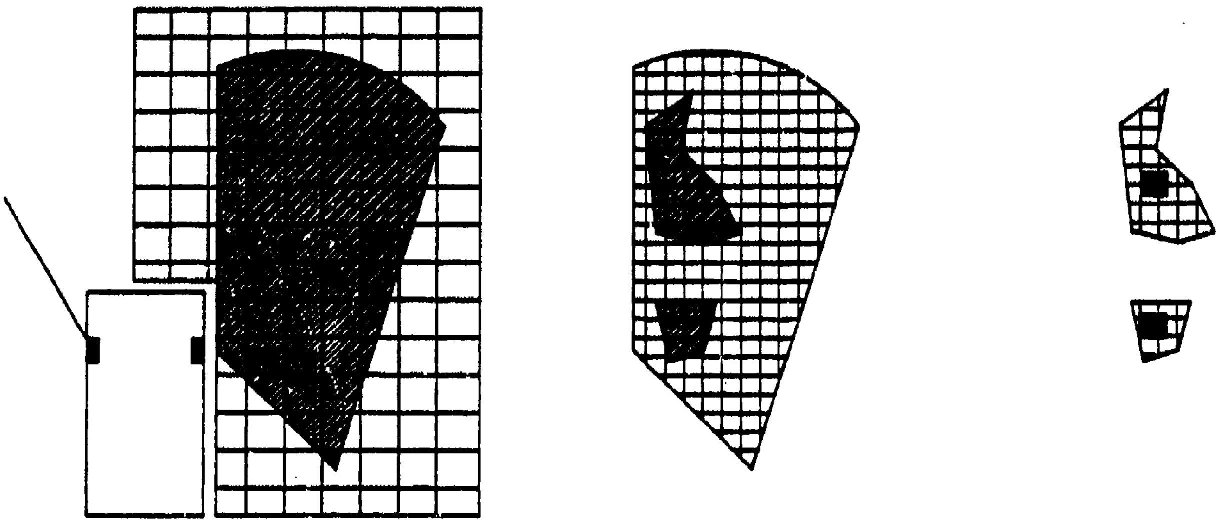
Within the utility decision subsystem, maps of higher spatial resolution are created for more detailed planning by enlarging the down-sampled map to the resolution of the incoming, sensed information. This results in highly redundant maps of increased spatial resolution. The scaling procedure is used to create, in the current system, maps at three levels of spatial resolution. The details of map-handling may be found in Quek and Franklin [5]. The subsequent evaluation of sensed terrain data for cost is modelled by a "virtual sensor," which acquires high resolution cost information from the original cost map in regions corresponding to those scanned by the visual sensor. Routes are generated at each level of resolution, the routing proceeding from coarsest to finest scale.

[3]The digital terrain database was produced by the Engineering Topographical Laboratories for the DARPA ALV program (DARPA Order No. 4670, Department of the Army Contract No. DACA76-84-C-0005) and furnished by Martin Marietta Corporation.

[4]Both types of terrain are shown in Figure 2, Appendix A.

While a route is defined as a "least cost" trail, in the subjective currency of the animal, a path is a sequence of acceptable footholds. The trafficability decision subsystem uses route information to direct the sensory systems to look for footholds. The actual selection of a path is subsequently governed by sets of rules defining footholds. Thus, although decisions at the utility level suggest a particular route, local foothold conditions may result in a path which deviates somewhat from the planned route. As described in the perception model above, the first step in foothold selection is the identification of sites within reach of the leg using low resolution vision. In order to simulate the detail of foothold selection near the animal, the reachable elements of terrain are expanded in resolution by a factor of four with a fractal algorithm. The second step in visual foothold selection is carried out on the new high resolution terrain elements only. Tactile evaluation is performed on those elements which pass the surface property test. Thus, foothold selection occurs at a spatial resolution four times higher than that at which initial reachability is assessed and at four times the resolution of the highest scale of utility assessment. The foothold selection process is illustrated in Figure 4 and discussed in the accompanying legend.

The CSAN simulation deals with large quantities of information and complex decision-making on distance scales from long-range route planning to local foothold selection. Such a simulation permits researchers to discover immediately whether assumptions generate realistic predictions, through extensive graphic displays of the vehicle's interaction with the environment and its decision-making processes (Figure 5). It has been run both on entirely synthetic terrain and on aerial map data of a small region of the foothills of the Rocky Mountains near Denver, Colorado. From the standpoint of pure science it allows the implications of assumptions about movement strategies and constraints to be discovered. From the applied standpoint it allows the investigation of animal or robot movements in representations of real environments.



1)Accessibility

2) Surface Characteristics

3) Surface Compliance

Figure 4.

Foothold Selection

Locating footholds for rough terrain traversal was simulated as occurring in three successive stages of sensing: 1) Low resolution visual information was used to determined the location of potential footholds within the reachable or accessible volume of a foreleg. 2) High resolution terrain was generated by creating four terrain elements from each accessible terrain element (see Section IV-A, Terrain Generation Tools). The resulting terrain was evaluated visually for surface properties, resulting in a reduced set of potential foothold. 3) A tactile test was applied to the foothold sites remaining, ordered in the direction indicated by the route specified by the utility decision subsystem. The first foothold in the direction of the route to satisfy the tactile test was accepted by the system.

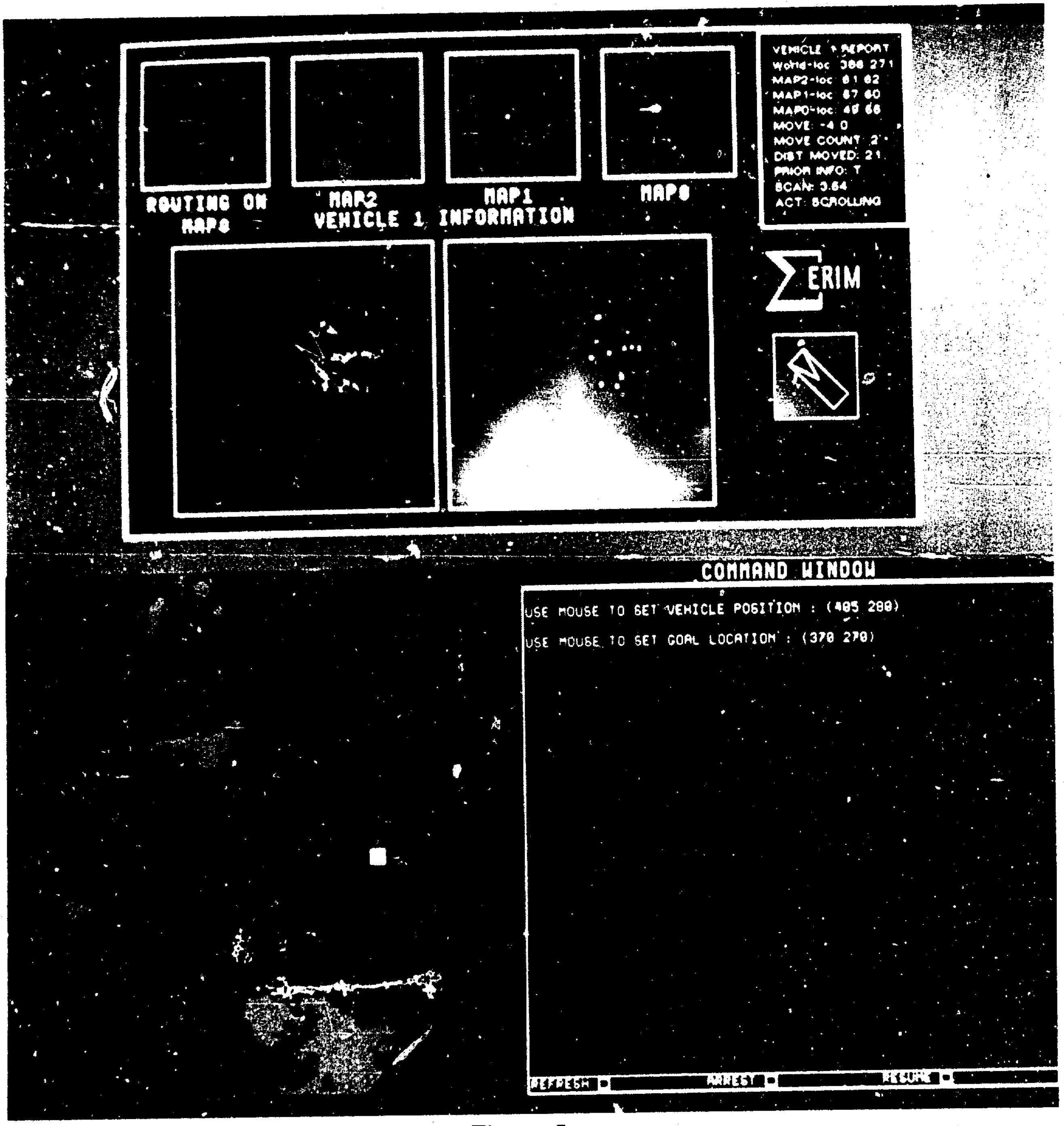


Figure 5.

Computer Simulation of Animal Navigation

In the lower left corner, the full (512 x 512) cost map is shown with the traversed path (highlighted in yellow) and the planned route as white dots. The goal location is marked with a white square. The upper half of the display includes both utility and trafficability levels of planning. The three cost maps, increasing in resolution from left to right, are displayed in the top row. The map currently in use for routing is duplicated on the far left. The trafficability level is shown below, with the current short-term memory on the left, including reachable areas (blue), potential footholds (pink), acceptable footholds (yellow) and footholds which failed the tactile test (orange). To the right is a grey-scale elevation map local to the vehicle, with acceptable and failed footholds marked.

4.0
THE BLACKBOARD PLANNING SYSTEM[5]

4.1 Limitations of the CSAN Planner

The CSAN simulation integrates long-range strategic (utility-level) and short-range reactive (trafficability-level) planning into a single decision framework [2]. As such, it represents a major advance in modelling the logical level of control required for mobility and navigation. There are, however, significant limitations to the CSAN planning system.

The first problem with the CSAN planner is that it is adaptive only on the trafficability (foothold selection) level. This stems from the fact that utility measures are applied to the terrain only before a simulation run. During a run, it is only the resolution of cost information that is modified. As a consequence, the results of sensing and terrain evaluation at the trafficability level cannot be reflected in revised cost maps at the utility level. All routing must be carried out on the basis of *a priori* cost information alone.

Unfortunately, *a priori* cost information may not lead to useable routes. In the decision model of Section 3.1 (Figure 3), utilities and costs are based upon motivational state, that is, the terrain is assessed with respect to some particular purpose. The factors upon which this assessment is based do not necessarily include terrain traversability. For example, regions of low ground might be of high utility (and correspondingly low cost) when considered for travel during concealment from predators. A route planned on such a basis might well lead through impassible ground (e.g. marshlands, river). In addition, the actual terrain conditions encountered may be different than those previously evaluated due to changes in the terrain and/or inaccurate or incomplete *a priori* information. A process therefore is needed by which to revise costs based upon the most recent and most accurate terrain information available to the planner. In this way, both utility and trafficability planning can be adaptive.

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[5]Portions of the Blackboard Planning System were supported by DARPA through subcontract to Martin Marietta (Contract No. GH4-116861) and through contract with the Department of the Army (Contract No. DAAE07-87-C-R001).

A second limitation of the CSAN planner is a consequence of the sense-plan-act cycle: body and non-contact sensor movements are determined solely by the planned route and current foot placement. Motion of the sensor(s) for the purpose of acquiring more information is not considered during planning. Visual sensing is therefore a passive process and path planning is necessarily constrained to the immediate vicinity of the utility level route, because the sensor field of view is centered on that direction. If no foothold is found within this region, the system fails. Since the route cannot be guaranteed to lead through traversible ground, as discussed above, the system must be able to actively move and sense for the express purpose of acquiring the information necessary to plan alternative routes and paths.

As these fundamental limitations of the CSAN simulation were examined, it became clear that they reflected, in part, limitations in the software architecture of the planning system. The rigid sense-plan-act cycle followed naturally from a sequential view of the planning problem, derived (at least in part) from working with sequential computers. All elements of the planning process must be stipulated in full detail with all temporal relationships between elements of the process specified in advance. Correcting these limitations within the existing CSAN framework would have entailed an extremely complex programming task and resulted in an elaborate piece of software with little room for future modifications. Breaking out of the sense-plan-act cycle in a robust fashion required an entirely different approach to planning, and correspondingly different software architecture. The architecture of most promise was the "blackboard architecture.

4.2 The Blackboard Architecture

The "blackboard architecture" (BBA) is really a class of software architectures built around a set of common elements. Blackboards have been developed for use in a variety of domains since their original implementation in the HEARSAY-II [6] and HASP [7] natural language understanding systems (see [8] for a review).

The elements which comprise a BBA are a global database (the blackboard itself), a set of knowledge sources (KS's) and a control structure (Figure 6). All data in a blackboard architecture are retained in the single blackboard database, which is typically structured in a hierarchical fashion corresponding to stages of problem-solving. Each KS encapsulates a portion of the problem-solving knowledge in the system. Knowledge sources are specified in a "condition-action" format. The action portion of a KS defines an algorithm, procedure, or other operation which contributes to problem-solving, and the condition component contains knowledge about when the action can be applied. Knowledge sources communicate strictly through the blackboard database.

Blackboard/KS interactions are regulated by the control structure. The basic control structure typically runs in a cycle of three distinct steps. First, the conditions for activation of each KS are compared against the data existing on the blackboard. Those KSs whose conditions are satisfied are grouped into a set of eligible KSs. Second, control rules are used to choose one or more KS from the eligible set. Finally, the chosen KS is activated, generating or modifying blackboard data. These steps are performed in a cycle until the blackboard indicates that a solution has been reached. Since there is no *a priori* restriction on the number of knowledge sources which can act simultaneously, multiple analysis paths can be pursued in parallel and abandoned as they are found to be fruitless. Uncertain and partial results arising from different processing approaches or from different sources can be combined at any point during the analysis, expediting progress to a solution.

4.3 Advantages of the Blackboard Architecture for Planning

Blackboard architectures have been explored in several autonomous vehicle programs, such as the Autonomous Land Vehicle [9] and the CMU Navlab [10]. Flexibility is crucial to systems which must respond adaptively to an uncertain and changing environment. The complexity and diversity of computational tasks required in planning and navigation requires distributed computing for real-time performance. The blackboard architecture was designed for flexibility in problem-solving and, as discussed below, is inherently parallel in nature. Some of the characteristics of the architecture which make

BLACKBOARD ARCHITECTURE

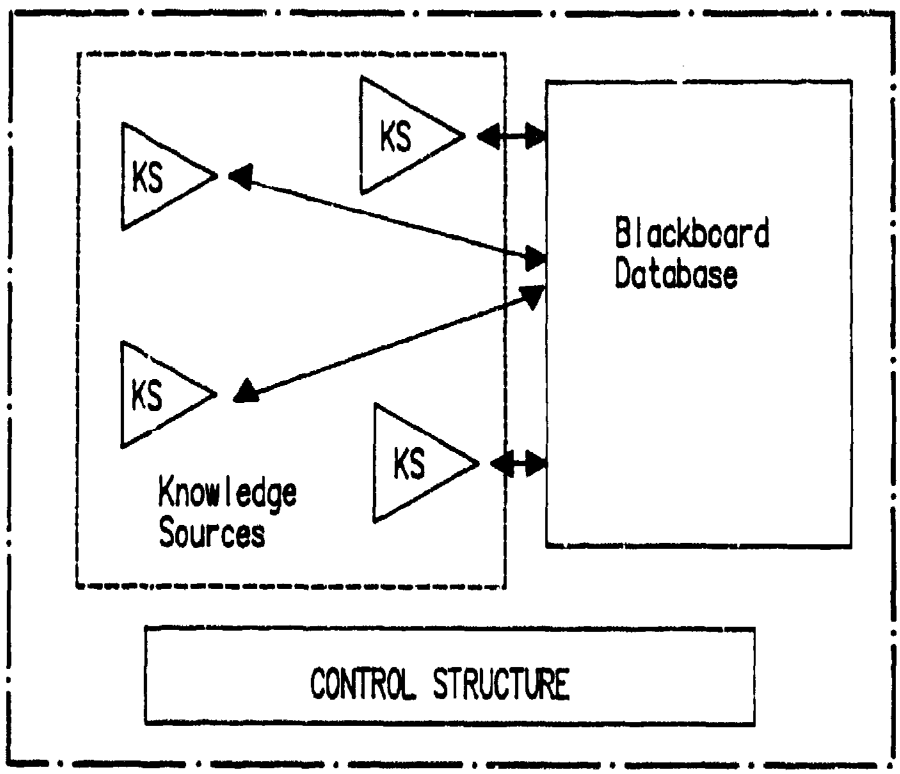

Figure 6.

Elements of the Blackboard Architecture

it particularly suitable for planning applications are outlined here. A comparison with alternative architectures was presented at a meeting of the American Institute of Biological Sciences [11].

Data and processing are separated in the blackboard architecture, by incorporating a single data repository (the blackboard) from which all processing elements (knowledge sources) acquire data. As a result, the same data may be processed independently for different purposes. This permits full flexibility in the flow of computation. For example, sensor data in the form of images may be processed for both texture and slope, and used to form an elevation map, without any interference between the different activities.

Knowledge sources in the blackboard architecture are entirely separate from one another; processing is therefore completely modular. In addition, knowledge sources can be implemented for sub-problems or tasks of arbitrary size and complexity. As a result, they can be tailored to the specific characteristics of each task that needs to be performed by the system. Sub-problems which occur as an element in a number of different tasks (such as updating maps, performing geometric transformations or routing on maps) can be can be carried out by a single knowledge source or by knowledge sources with identical action components and different conditions. Alternative approaches to a single task (such as texture evaluation algorithms of differing accuracy) can be implemented as different knowledge sources which operate on the same data under various conditions. Similarly, knowledge sources can be designed to carry out tasks at various levels of abstraction, depending upon the immediate requirements.

The modularity of the processing in a blackboard architecture means that it can support any desired degree of parallelism or concurrency. Not only can the same data be processed for different purposes, but this processing can occur simultaneously. This is essential for navigation, in which so many different activities are required: sensory data are continuously acquired and must be processed to meet current planning needs; local and global path planning and revision must proceed based on the latest information; the status of the vehicle and environment must be continually monitored. Limiting these tasks to sequential execution would not only be hopelessly inefficient, but would also fail to allow

the vehicle to respond to changing conditions in the environment, some of which may be emergencies requiring immediate action.

The independence of knowledge sources from each other and from the database means that the architecture can be implemented on an arbitrary set of computers, taking advantage of a heterogeneous distributed computing environment with specialized processors for different aspects of planning. Just as knowledge sources can be implemented on different processors, the global database itself can be distributed over several machines. Diverse data types can still be integrated within a single data structure, as far as the system is concerned. To the system designer and to the architecture itself, the distributed character of the hardware implementation is transparent.

A very important additional advantage of the blackboard architecture is that it facilitates incremental or evolutionary system development. Knowledge sources can be implemented first in simple forms and then upgraded as desired. New capabilities can be added without perturbing existing knowledge sources. The modularity of the architecture makes it easy to maintain, an important feature in any software system of the sophistication required for autonomous terrain traversal.

4.4 Implementation of the Blackboard Planning System

As a first step, a planning system with a simple sliding vehicle model was developed in the blackboard architecture. The modularity of the architecture permits the substitution of a legged vehicle model with few modifications. The 2-level planning model of the CSAN simulation was implemented in two blackboards, each residing on a Symbolics computer (a 3640 and a 3670). The diagram in Figure 7 is an overview of the Blackboard Planning System. The two levels of planning are utility (global, mission-based planning) and trafficability (local planning) which considers terrain and vehicle characteristics in the selection of a path. The utility level of planning involves two major tasks: mission-based route generation and cost-map maintenance. The trafficability level consists of the following tasks: terrain evaluation, local memory maintenance, path planning, and path to motion conversion. A group of knowledge sources has been developed for each of these tasks.

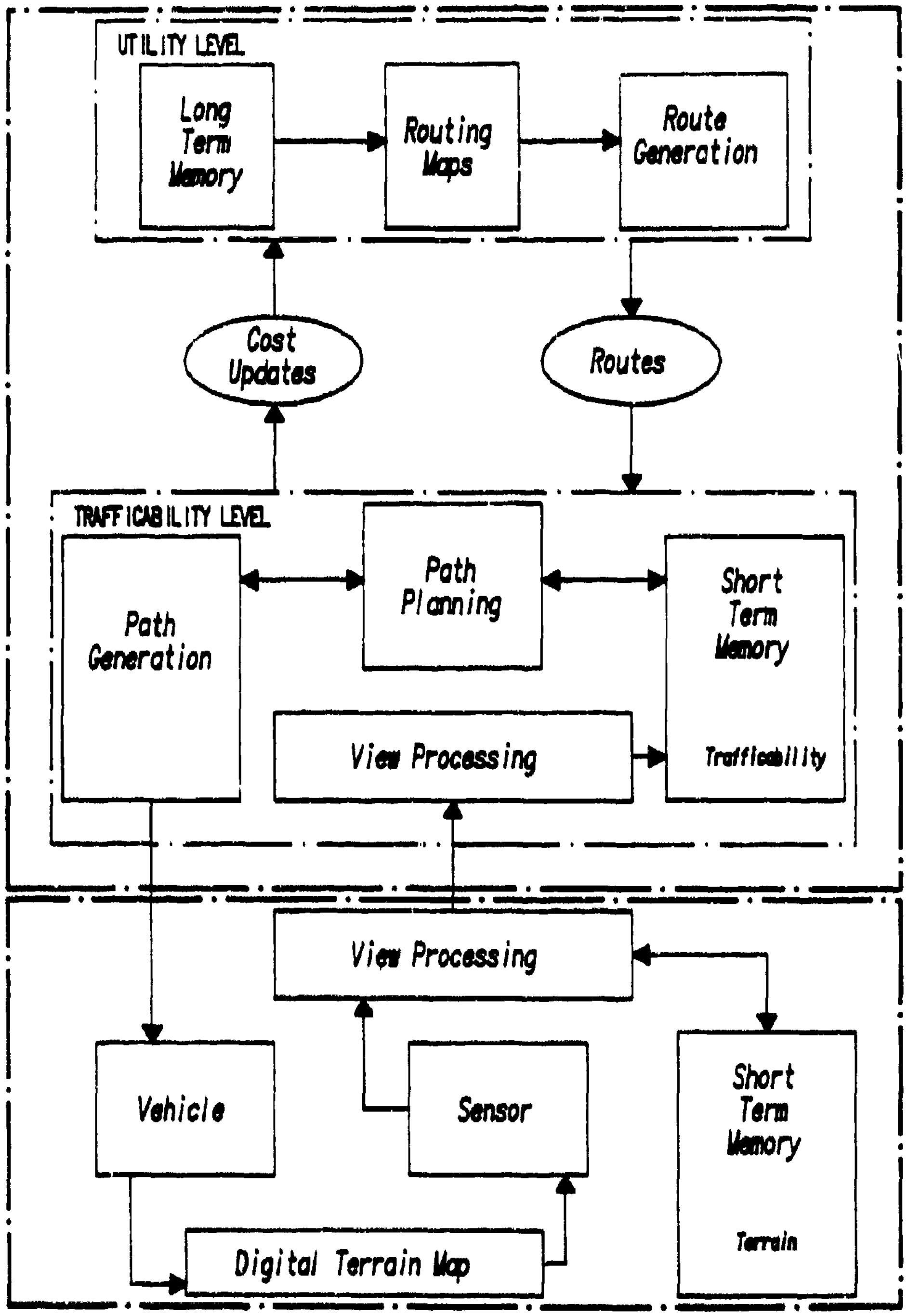

Figure 7.

Schematic of the Blackboard Planning System

In the original (CSAN) simulation, the only interaction between the two planning levels was via routes generated at the utility level and transferred to the trafficability level. There was no means of recovery if no footholds were found in the trafficability layer. Since no mechanism was implemented to update the utility level maps with foothold data, the utility level planner was unable to generate paths different from those that failed. In the new system, the loop is closed by transforming and transferring local terrain information having navigational value at the trafficability level to cost information at the utility level.

Four modes of operation, or behaviors, were specified in the Blackboard Planning System: normal, retry, detour and replan. Normal mode corresponds to the single behavior implemented in CSAN. Retry, detour and replan are increasingly extreme measures to recover from failure to find a traversible path. In retry mode, all currently available sensory data are incorporated into the local elevation map and an attempt is made to replan on the path level with this most up-to-date information. Detour entails moving the vision sensor to scan the terrain all around the vehicle. The newly acquired terrain information is then updated into the local map and a new path is derived. Replanning requires that all information from the (updated) local map be transformed into the cost maps, from which a new route is obtained. The modes are intended to be used sequentially, with failure in one mode triggering the next; success in any mode triggers a return to normal operation.

The Blackboard Planning System was built in a framework developed for a road-following context.[6] The basic blackboard framework structure will be outlined here; it is described in more detail in Finzel and Harmon [12].

Blackboard Database. The global blackboard databases were implemented in hash-table structures. Hash-tables are extensively supported by Symbolics software, with built-in hashing functions for efficient searches. Add and delete functions which avoid low-level read/write conflicts are available. The size of hash tables changes dynamically and automatically, permitting flexible allocation of space to different types of data. Symbolics

[6]Work supported by U.S. Army Tank Automotive Command under Contract DAAE07-84-C-R138.

hash-tables can store any kind of Lisp object, which means that data elements can be of any type, including lists, arrays, numbers and other hash tables. This is an important aspect of the database for a complex decision system such as the BPS.

Both databases in the BPS were implemented as a set of nested hash tables (Figure 8). Within the table containing the entire database (*bb*), there are tables for each level of the decision model ("utility" and "trafficability"), as well as for vehicle and world information ("vehicle"), and for control of the blackboard ("administration"). Each of the "level" tables contains a set of "type" or data tables, which store the actual blackboard data. Although the table structure itself is hierarchical, there is no explicit hierarchy among data tables.

Knowledge Sources. Two types of knowledge sources were incorporated into the BPS: regular and control. Regular KSs perform all of the computational and reasoning tasks associated with sensing, route- and path-planning, motion and map updating. Suites of regular KSs were developed for each desired mode of system operation (or behavior), for example normal mode and retry mode. Control KSs monitor the state of the vehicle and planning system to determine the appropriate mode at a given time. Modes are changed in response to specific conditions, such as the failure to find a traversible path along a planned route. Control KSs effect changes in behavior or mode by altering the suite of "active" or "available" KSs. These changes are transparent to the remainder of the planning system.

Control Module. The control structure of the BPS was implemented as a simple production system. At each cycle, all active KSs are checked to determine which can be invoked, based upon the state of the blackboard. The entire list of eligible KSs is acquired and the first KS on the list invoked. Priority among KSs is established only by an *a priori* ordering of the active KS list. Flexibility in overall system behavior is therefore accomplished solely by altering the set of available KSs to be checked. An important research issue that became clear during implementation of the BPS is the development of control components which can truly exploit the inherent flexibility of the architecture. Hayes-Roth [13] has addressed this issue by implementing the control module as a separate

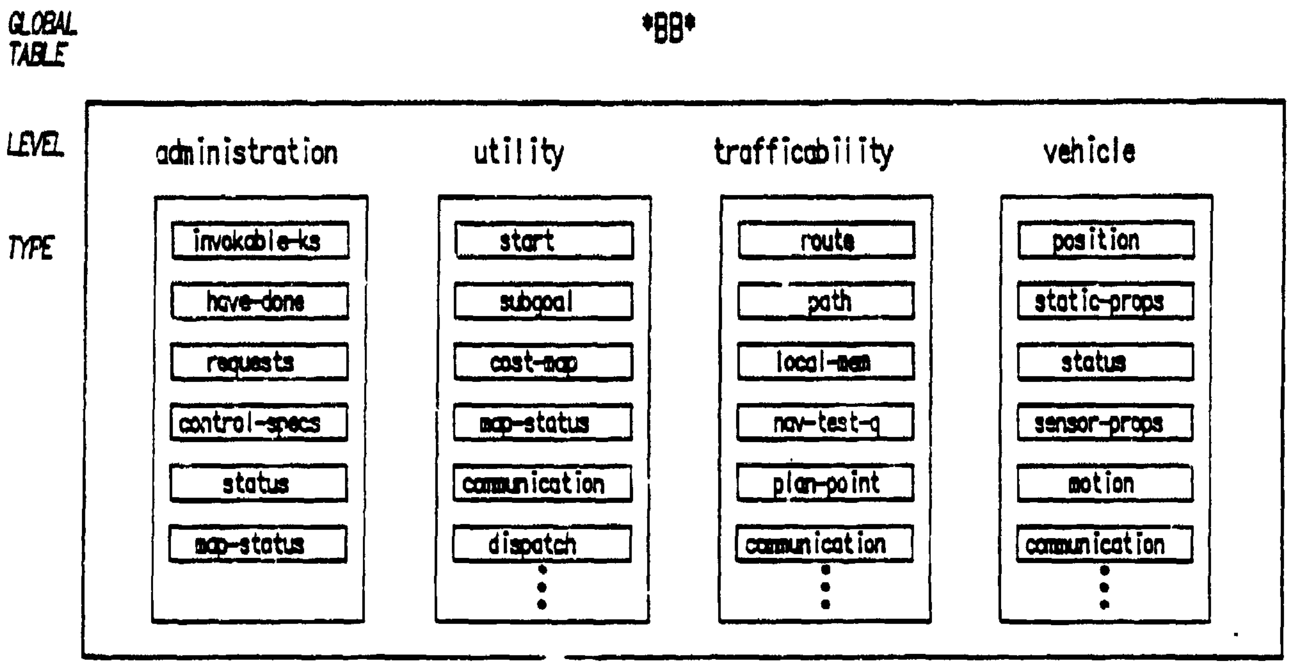

Figure 8.

Organization of the Blackboard Planning System Database

blackboard; while useful in some contexts, this approach simply shifts the fundamental question to the control module of the control blackboard.

Other components of the system and software tools were developed which are not strictly part of the blackboard architecture itself, including a vehicle model and a sensor model; these are discussed further in Section 5. Both vehicle and sensor models as well as the blackboard supporting the tasks of maintaining elevation data in local memory and early stages of terrain evaluation (sensor view processing) were implemented on the Symbolics 3670 (see Figure 7). The Symbolics 3640 supported the blackboard that manages tasks at the utility level of planning, final stages of terrain evaluation, maintenance of navigational information in local memory, path planning, path to motion conversion, as well as data transfer between the trafficability and utility levels of planning (Figure 7).

Communication services were developed using TCP/IP to transfer data between the two machines in support of this distributed system. Two of these services transfer processed sensor images from the Symbolics 3670 to the Symbolics 3640. Another service transferred motion commands back to the Symbolics 3670 that supported the vehicle model.

In the original legged vehicle simulation, high resolution terrain data were generated when required by the vehicle's path planning module. Excessive time was required to perform this process and therefore we have developed a more time- and space-efficient method to maintain high resolution terrain data in the blackboard planning system. Two pre-generated terrain maps, consisting of the underlying topology and high frequency surface characteristics, are maintained on the Symbolics 3670. At the time of scanning, data from these two maps are combined in the region covered by the sensor view to form 16-bit elevation data. These data are evaluated according to slope and roughness and the resulting 4-bit data are sent to the second Symbolics using TCP/IP. Although retrieval time of high resolution data is influenced by network performance, it is less than the execution time of the method currently implemented in the legged vehicle simulation, that of frequent terrain generation.

4.5 Status of the Blackboard Planning System

The blackboard planning system described above is currently unfinished. Although the blackboard architecture itself supports concurrent operation of multiple knowledge sources, mechanisms for controlling concurrency must be implemented separately. In a system of this complexity, concurrency became a very real problem, as evidenced by one knowledge source causing undesirable and excessive activity in other knowledge sources. In order to remedy this problem in the blackboard supporting the utility level of control, a new flag structure was built; the state of one or more flags may be used to determine whether or not a knowledge source may be invoked. Also, a subset of the relevant knowledge sources was rewritten to comply with this new structure. Similar changes must also be made in the blackboard supporting sensor view processing. This interim mechanism solves most of the problems encountered in the system, although two or more knowledge sources may attempt to alter the same flag at the same time. The results of such actions cannot be predicted and yet they must be avoided. In order to produce a completely reliable system, a robust protocol for dealing with problems of concurrency must be developed. Appropriate changes must then be made to the system in order to realize this protocol in the blackboard planning system.

A second issue raised during the development of the blackboard planning system is how to implement the control element of the blackboard so as to maximize the flexibility of the resulting decision system. The current implementation of the control module as a production system is well-defined, but does not respond well to changing priorities. Replacing suites of knowledge sources is an effective way to accomplish global, system-level, changes in behavior. In addition, however, more sophisticated mechanisms to change the priorities of individual knowledge sources in response to less drastic external conditions, and to system resource usage, are required to fully exploit the potential of the blackboard architecture in planning applications.

5.0
RELATED SOFTWARE DEVELOPMENT

Several pieces of software were developed in conjunction with the simulations described above. These included tools for generating synthetic terrains, a simulation of the ERIM 3-D laser scanner, tools for inter-computer communication over Ethernet and graphics modules.

5.1 Terrain Generation Tools

In support of the CSAN and BPS computer simulations described above, several techniques were developed to generate simulated terrain.

Fractal Surfaces. A program was written to create fractal surfaces using a randomized mid-point migration strategy. An attempt was made to write this program in C on a PC-AT. It was decided that the PC-AT was too slow and the addressable memory too limited for the purpose and an improved version was written to run on the Symbolics. This version of the fractal generation program was completed and used to generate synthetic terrains for the simulations described in the previous sections.

The sensing and perception model discussed in Section 3 required elevation data at multiple levels of spatial resolution. The memory requirements for storing full elevation maps at high resolution and down-sampling to low resolution were prohibitive. Two different methods of generating high resolution from low resolution data were devised. In the CSAN simulation, high resolution terrain data local to the vehicle were generated from the low resolution map when required by the vehicle's path planning module. A deterministic fractal expansion algorithm was used for this purpose which consumed a substantial fraction of the available computing resources.

A more time- and space-efficient method to handle high and low resolution terrain data was developed for the blackboard planning system. Two pre-generated (8-bit) terrain maps were maintained. One consisted of the underlying topology, at low resolution in both

the x-y plane and in elevation. High frequency surface characteristics were stored in a high resolution map spanning a smaller extent in the x-y plane. Elevation values in the high resolution map corresponded to the lower order bits of the actual elevation at each point. At the time of scanning, data from low and high resolution maps were combined in the region covered by the sensor view to yield 16-bit elevation data at high resolution in the x-y plane. By pre-processing these data according to slope and roughness, they were reduced to 4-bit data before being sent to the second Symbolics using TCP/IP (see Communication Tools, below). Even allowing for pre-processing and variations in network performance, this method was faster than the method of high resolution terrain generation employed in CSAN.

Terrain Editor. In order to produce terrains with a wider range of characteristics than the fractal surfaces, a terrain editor was built. This program gives an experimenter the ability to create and manipulate complex, synthetic terrains in the form of relief or elevation maps. The program has an interactive interpreter front-end which processes high level user commands. Pixel and neighborhood processing operations can be performed on the entire terrain or on specific regions. Terrains can also be combined with a variety of operations. Commands were implemented to retrieve and store terrains as arrays in files.

The body of the terrain editor is a set of subroutines which facilitate the addition of terrain features (e.g. roads, landmarks, and barriers). Commands are available for drawing objects such as lines, arcs, and three-dimensional shapes. Arbitrary lines can be drawn with a mouse. The terrain editor was built with expansion and the capability of adding new terrain objects in mind. In order for others to make use of the terrain editor software effectively, extensive documentation was written for the system. A draft of this document was completed which included the level of detail necessary for others to expand the system. Both source code and documentation have been delivered to the sponsor.

5.2 3-D Laser Scanner Simulation

The CSAN simulation was developed on Symbolics machines in ZetaLisp, but several elements are better suited for general purpose computers using a language such

as C. As a first step towards a distributed heterogeneous computing environment, a single component of the simulation was selected to be run on a second machine: the sensor model. The visual sensor model used in the original CSAN simulation was rudimentary. Within the sensor field of view, complete and perfect knowledge of the terrain was acquired. A more realistic model would present the planning system with the fundamental problem of incomplete and uncertain information through the introduction of occlusion in sensor views.

A ray trace program that simulates the ERIM 3-D range sensor had already been written in C for a VAX/VMS system. For the project reported on here, a version of the program was developed to run on an IBM PC-AT. This version of the 3-D sensor simulation was demonstrated by invoking it from the Symbolics computer. The PC-AT graphics display of the sensor simulation included a portion of the map to be scanned, plan view (X-Y plane) of the scanned region, and an angle-angle-range image of the scanned region. Scanner views were displayed in modulo 15 format on the EGA (Enhanced Graphics Adaptor) display. A color look-up-table (LUT) was written for display purposes.

It was soon found that the PC-AT was not powerful enough to handle the amount of sensing required by the simulation on the Symbolics. Therefore, the 3-D sensor simulation was revised for a SUN 3/110 computer. As discussed below, network difficulties prevented demonstration of the SUN 3-D sensor simulation in conjunction with the Symbolics computers.

5.3 Communication Tools

Distribution of the computer simulations required the development of tools to allow the Symbolics machines to communicate with either PC-AT or SUN computers. The Symbolics machines at ERIM were on CHAOSNET which is not supported in C, the language of choice on the other computers. Work was therefore undertaken to convert the networking system to TCP/IP. Software communications tools were written which utilized TCP/IP to invoke the sensor simulation from a Symbolics. These tools were incorporated

into a demonstration of the sensor simulation which is invoked from the Symbolics while running on a PC-AT.

Network communications tools similar to those above were written for a SUN and integrated with the 3-D simulation on the SUN in order to invoke it from a Symbolics computer. Data transfer between the Symbolics and SUN was found to be too slow for effective use of the distributed sensor simulation in either the legged vehicle simulation (CSAN) or the blackboard planning system (BPS). The hardware and software were tested extensively in order to determine the source of poor network performance. Although Symbolics to Symbolics communication was greatly improved, Symbolics to SUN data transfer remained slow and inconsistent. Further refinement would be required to integrate the SUN version of the 3-D sensor simulation into CSAN or BPS.

The blackboard planning system (BPS) was distributed over the two Symbolics machines. This required extensive communication between the two computers. Communication services were developed using TCP/IP to transfer data between the two machines in support of this distributed system. Two of these services transfer processed sensor images from the Symbolics 3670 to the Symbolics 3640. Two other services transferred motion commands and status information back to the Symbolics 3670 that supported the vehicle model. The communication services were implemented as free-running processes in Zetalisp. Send and receive buffers for each service were located in separated tables in the blackboard database on the appropriate machine.

5.4 Graphics Development

Work was initiated on a graphics module for the CSAN simulation in order to provide perspective views of the terrain and the vehicle. However, in working with the University of Wisconsin, it became evident that software had already been developed to provide views of the vehicle. Therefore, ERIM's work concentrated on perspective views of the terrain alone.

It was decided that the graphics module would be written for a PC-AT. The resolution required for adequate representation was studied and it was determined that the

EGA (Extended Graphics Adaptor) then on the PC-AT was not suitable. The PGA (Professional Graphics Adaptor), a vector graphics board, was chosen and installed in the PC-AT. Software was written which uses this board to display the terrain generated, both as pixel-wise scatter plots and facet displays.

Examination of the large quantity of information in the CSAN simulation required the design and implementation of a color-graphic, animated display system, as shown in Figure 5. Both utility and trafficability levels of planning are represented in the display, as well as the details of the terrain and vehicle motion. Without a display of this nature it would have been impossible to determine moment-to-moment activities and hence the system performance in complex domains.

As part of the blackboard planning system, two other displays were developed. One (Figure 9) showed the world map of low resolution elevation data and the high resolution elevation information in the vehicle's local memory, obtained through sensing. A color map was designed which allowed the full range of elevation values to be represented by a combination of grey scale and hue. The second (Figure 10) represented the activity of the blackboard planning system.

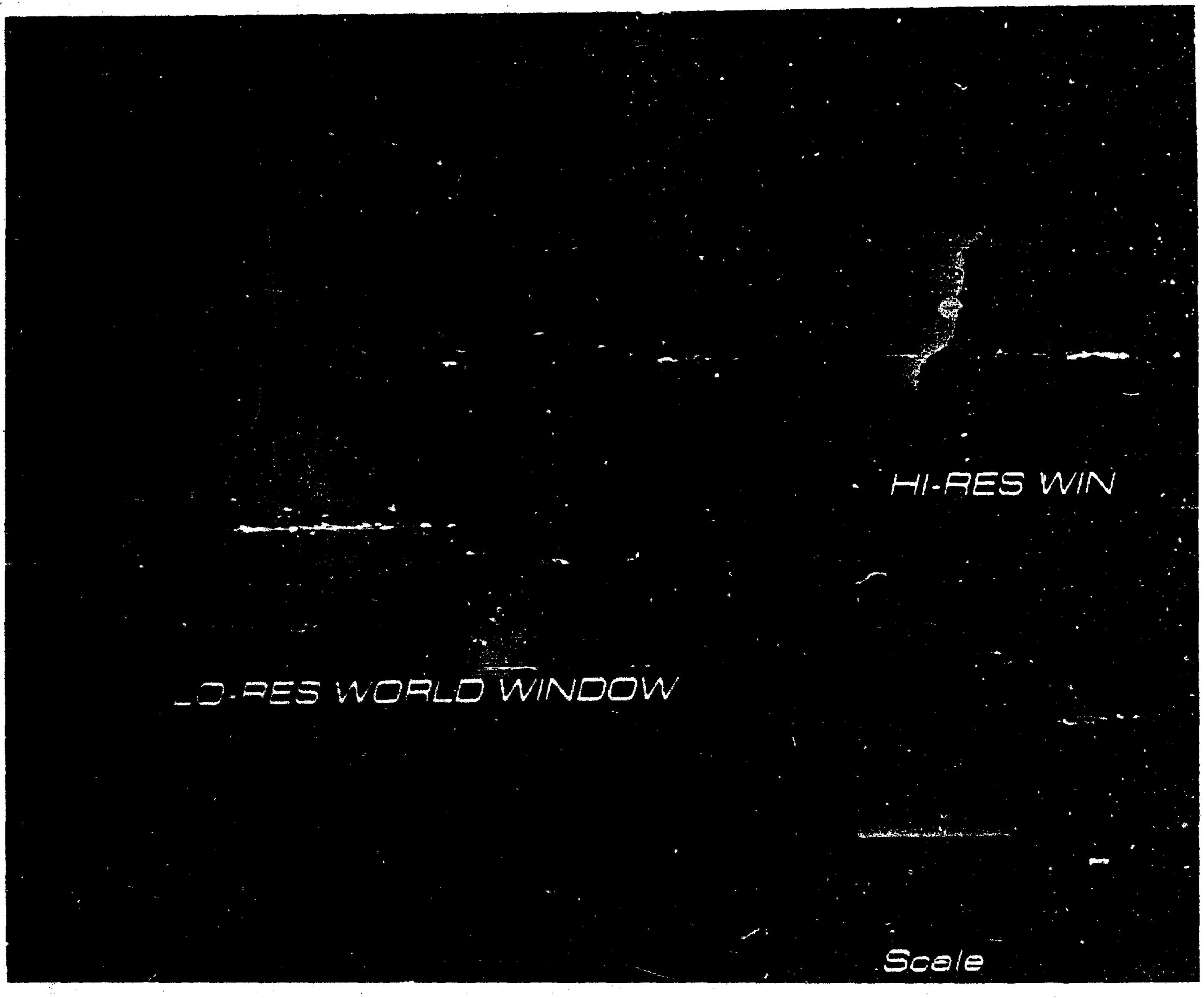

Figure 9.

Terrain Maps in the Blackboard Planning System

The low resolution world map (a fractal terrain) is shown in the upper left as a grey scale image. The path traversed by the vehicle is superimposed on the map. In the upper right, high resolution elevation data acquired by the vehicle during sensing are shown, using the color scale indicated below. Elevation proceeds from light green (low) to dark red (high).

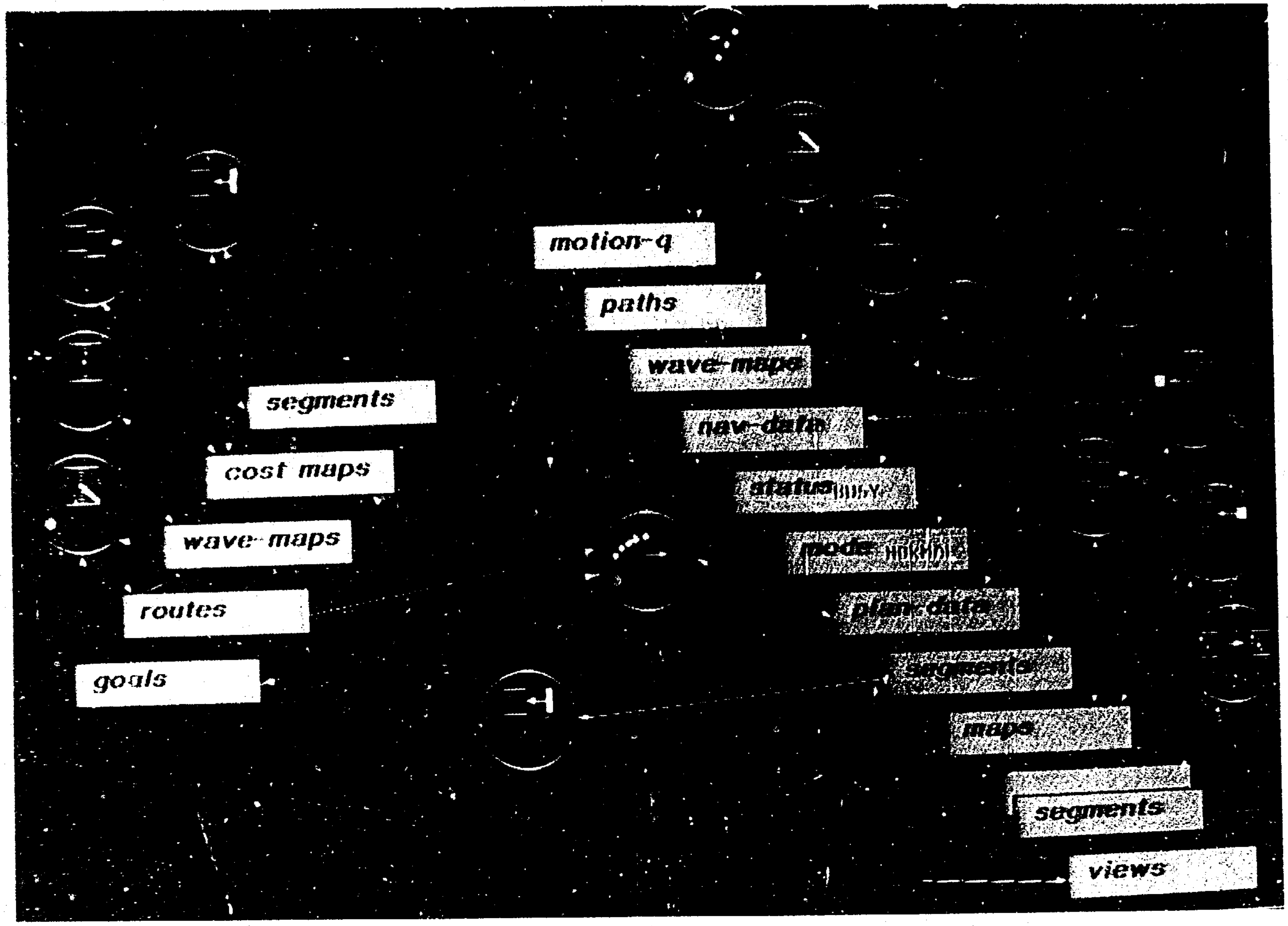

Figure 10. The Blackboard Planning System

The primary activities of the BPS are shown in this display (from the Symbolics 3640 color monitor). Blue rectangles represent data tables or groups of tables, while circles with icons represent knowledge sources or groups of knowledge sources (KSs). The flow of data is indicated by arrows. Red or blue dots within the KS circles denote KSs which are operating or invokable, respectively. The utility level of planning is shown at left, with trafficability to the right. KSs which connect the two are represented in the center. Connections to the sensor and vehicle simulations on the other machine may be seen in the arrows leaving "motion-q" (near the top) and entering "views" (near the bottom); these correspond to motion commands and partially processed sensor data, respectively.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The research reported here has served to further the understanding of autonomous navigation of rough terrain through a study of ungulate locomotion leading to the development of a decision model and implementation of the basic decision model in computer simulation (CSAN). Development of the Blackboard Planning System was directed toward a flexible control system with the potential to direct fully autonomous navigation in unfamiliar terrain. While this system is incomplete, the work has served to lay important groundwork and reveal critical research issues which must be addressed in the future.

- Robust protocols are needed to manage concurrency in complex parallel decision systems, whether implemented on single or multiple computers.
- Further research is required to develop mechanisms for controlling blackboard systems so as to maximize flexibility and adaptiveness in their operation.
- Research on the current program did not address the on-going evaluation of terrain with respect to motivational state. This will be an increasingly important issue as the tasks or missions envisioned for autonomous vehicles become more elaborate.

7.0
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13. Hayes-Roth, B., 1985. "A blackboard architecture for control," Artificial Intelligence 26, 251-321.

APPENDIX A

AI Simulation of Search and Exploration Behaviors

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Preface

The research described in this report was made possible through subcontracts with the University of Wisconsin and Martin Marietta Corporation (subcontract numbers 208G-762 and GH4-116861). The University of Wisconsin mission to provide research on autonomous land traversing capabilities for the ASV has been supported by the Defense Advanced Research Projects Agency (DARPA) through contract with the Department of the Army[1]. The Martin Marietta Corporation has been funded for development of the Autonomous Land Vehicle Project by DARPA through contract with the Department of the Army[2]. The findings and conclusions presented in this report do not necessarily represent the views of the above agencies.

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1. Reference: DARPA Order No. ARPA-5575 and Department of the Army Contract No. DAAE07-86-C-R013.

2. Reference: Department of the Army Contract No. DACA76-84-C-0005.

Chapter 1

Introduction

A key element in the mobility of mammals is the ability to locate terrain which is suitable for, or which affords[3] traversal and to retain information about this terrain in, what is commonly called, a cognitive map[4]. For the purposes of this study, the process of traversal is modeled as occurring at two fundamental levels which we will refer as:

1. a route which is a sketchy plan for traversing long distances[5]. Routes are generally based on prior information and are formed from a general knowledge of the terrain. Since animals live in dynamic circumstances, a highly detailed route would not make sense since some of the information would be out of date by the time it was used.

2. a path which is a detailed plan for traversing short distances. Paths are based on highly detailed information, a combination of prior information and current sensory activity and are generally biased by route selection information. Thus, in a sense, a route is the predictive element in a traversal plan and a path is the adaptive element.

It should be noted that there are some difficulties associated with formulating a precise definition of the extent or domain of a path. Where do paths leave off and routes begin? It is a purpose in building this model to explore these issues. Thus, they have not been solved or defined in any way other than arbitrarily (although reasonably) at the outset, with the idea that they may be changed as the research progresses.

Experiments with Nubian goats have demonstrated that they search for suitable footholds using two sensing modalities and a particular set of leg movements in order to traverse rough

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3. Gibson, J.J. 1958. Visually controlled locomotion and visual orientation in animals. Brit. J. Psychol. 49:182-194.

4. Tolman, E.C. 1948. Cognitive maps in rats and men, Psychol. Rev. 55, 189-208.

5. We mean here to refer to the ability to traverse long distances, well beyond the range of vision and olfaction, such as when herds of ungulates migrate.

ground. Information about footholds and the general path taken are both retained and used to guide traversal in subsequent crossings.[6] These activities are the basis for path selection by these experimental animals and a computer model has been constructed of this behavior. This simulation has concentrated primarily on the process of identifying and locating suitable footholds on terrains of arbitrary complexity. As such, it represents a model of a search activity for a resource which, like other resources in the environment is more or less scarce.

Theoretical work on decision systems for robot vehicles has demonstrated that machine autonomy depends critically on an ability to identify and locate information which is missing from a terrain knowledge-base[7]. Implementation of heuristics for extending the knowledge-base enables the machine to complete a given mission. Both search and exploration (defined below) are essential heuristics in this respect. As a part of this theoretical work, a computer simulation was built to examine the key decision-making elements of trail formation (blazing) and subsequent use of the trails for trail following. This has been combined with simulations of ungulates traversing rough terrain[8] to investigate the role which search and exploration play in successful terrain traversal. The objective of this paper is to present three aspects of this work:

1. Definitions will be presented for search and exploration behaviors and their role in locomotion will be described.

2. A model will be presented which is used to assemble and test elements which are critical for traversing terrain of high spatial and temporal complexity.

3. Two simulations will be presented, one which addresses searching for suitable footholds and another which uses exploration in a trail finding context.

This work has made extensive use of AI programming techniques, including object oriented programming and the ability of AI working environments to address problems having large information spaces (Franklin & Taylor, in press). Particular emphasis will be placed on those aspects of the work which rely on the logical framework provided by this type of computing environment.

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6. Franklin, R. & Leon, L. 1987. Studies of Ungulate Locomotion 1984-1986: Final Report for contract RF452622 with Ohio State University (TACOM contract DAAE01-84-K-R001).

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The literature dealing with these behaviors, which we suggest are critical to the execution of terrain traversal, includes theoretical and experimental studies from the fields of ethology and psychology. The subjects of the studies range from invertebrate to human. One component of the body of literature seeks to distinguish, define and model specific behaviors such as orienting, search, exploration, and patrolling. A second component accepts as given the existence of particular behaviors in order to study elements such as cognitive maps and search images. In both of these areas some attempts have been made to address the purpose of these behaviors and their costs and benefits.

Delineating specific behaviors is a difficult task. For each distinction which is suggested both supporting and conflicting experimental evidence is available[9,10]. Birke and Archer[11] attribute a part of this difficulty to the fact that these behaviors are first defined by their primary function of obtaining information and this consequence is not tied to any one specific motor act. Yet the need to rigorously distinguish amongst forms of these behaviors remains, if for no other reason than to establish uniformity in the terminology used by researchers in the several disciplines.

Exploration is the primary term used in the literature for these behaviors. Berlyne[12] sought to make explicit distinctions as to types of exploratory behavior (reviewed and discussed by Russell[13] and Inglis[14]). Berlyne distinguishes between extrinsic and intrinsic exploration; extrinsic exploration is an activity in which there is an obvious goal or link to a specific need, while intrinsic exploration has no apparent goal other than the general purpose of gathering information. We have chosen to use the term investigatory behavior as analogous to Berlyne's most general term, exploration. As have others[15], we use the term search in place of Berlyne's

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term extrinsic exploration and refer to intrinsic exploration simply as exploration[16]. Thus, search can be included with existing theories of drive or motivation in that a specific requirement can be identified as a goal. A larger problem lies in defining and modeling exploration.

Initial attempts to model exploration began by including it in general models of motivation, which included such drives as curiosity and boredom drives[17]. While data were found to support each of these drives, data were also found to refute each. Other models sought to identify either internal or external motivational factors. Drive theory assumed that the presence of novelty in the environment acted as a stimulus to exploration, however, experimentation primarily in the laboratory, has shown both increasing and decreasing tendency to explore as novelty increases. Birke and Archer[18] argue that measuring novelty is very difficult in that novelty is relative to the particular past experience of the individual being tested, as well as the animal's immediate internal state and the context in which the novel stimulus is being presented. Toates has reviewed this literature and found such models to be inadequate[19]. He prefers an approach described as incentive-motivation theory in which internal states set limits on, or accentuate, the strength of external stimuli to arouse behavior. Toates presents evidence for a cognitive model of exploration. The cognitive approach views exploration as a behavior serving to build representations of objects and events in the environment, the establishment and maintenance of cognitive maps. Support for this approach can be found in both the ethological and psychological literature[20,21,22,23].

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16. Berlyne also made distinctions between specific and diversive exploration and between inspective and inquisitive exploration. Review of these definitions suggests that there is overlap in the behaviors described. Laboratory and field experimentation would be needed to analyze the validity of the distinctions drawn by Berlyne and the further interpretations of these distinctions by others.

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23. Bruno Poucet, Catherine Thinus-Blanc, and Nicole Chapuis. 1983. Route Planning in Cats, in Relation to the Visibility of the Goal. Animal Behavior. 31:594-599.

While the purpose of the investigatory behaviors, search and exploration, is generally viewed to be the gathering of information by which to reduce uncertainty about a stochastic environment[24,25,26,27], most discussions of costs and benefits of exploration are theoretical. The costs of these behaviors are seen to be primarily the expenditure of energy which could be used for other purposes and an increased risk of predation. Among the benefits suggested are reduction of uncertainty, establishment and maintenance of a familiar home range, and anticipation of remote events through knowledge of a world model. These benefits purportedly result in an ability to respond appropriately and adaptively to a changing environment.

Gibson proposes an integral role for search and exploration in locomotion[28] with exploratory behavior having perceptual, motor, and knowledge acquiring aspects. She emphasizes that even the perceptual component is active and that actions tend to reveal new information, the motion inherent in terrain traversal in itself being part of or contributing to the exploratory process. Movement allows for discovery of affordances in the environment and the building of cognitive maps. The existence of cognitive maps then aids in adaptive planning for future terrain traversal.

Since our interest in search and exploration derives from a desire to better understand terrain traversal capabilities in animal, this goal influences our view of investigatory behaviors. We have not tried initially to derive thorough models and definitions which are relevant to all possible uses of such behaviors. Instead we have tried to gather from the work of others, those elements of these behaviors which appear to be used in terrain traversal, expecting that a detailed knowledge of these behaviors as they relate to locomotion will assist in understanding them in a broader context.

As a final note, one of the struggles seen in the literature is desire to determine whether or not separate types of investigatory behavior exist. Importantly, several authors identify the likelihood that even if separate behaviors can and do exist, they may in fact most often act in

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24. Russell, P. A. 1983. Psychological Studies of Exploration in Animals: A Reappraisal. In: Exploration in Animals and Humans. John Archer and Lynda I. A. Birke (eds). Van Nostrand Reinhold (UK) Co. Ltd.

25. Birke, Lynda I. A. and John Archer. 1983. Some Issues and Problems in the Study of Animal Exploration. In: Exploration in Animals and Humans. John Archer and Lynda I. A. Birke (eds). Van Nostrand Reinhold (UK) Co. Ltd.

26. Eleanor J. Gibson. 1988. Exploratory Behavior in the Development of Perceiving, Acting, and the Acquiring of Knowledge. Annual Review of Psychology. 39:1-41.

27. P. E. Cowan. 1983. Exploration in Small Mammals: Ethology and Ecology. In: Exploration in Animals and Humans. John Archer and Lynda I. A. Birke (eds). Van Nostrand Reinhold (UK) Co. Ltd.

28. Eleanor J. Gibson. 1988. Exploratory Behavior in the Development of Perceiving, Acting, and the Acquiring of Knowledge. Annual Review of Psychology. 39:1-41.

unison[29,30]. For example, an animal can gain general information about the environment while searching for a specific food item or nesting material. Recognition of the concurrent nature of such behaviors is critical to building realistic models and poses special challenges to modeling such behaviors on sequential computers. It may be this tendency for a variety of behaviors to act concurrently that makes definition of separate behaviors often seem arbitrary.

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29. Birke, Lynda I. A. and John Archer. 1983. Some Issues and Problems in the Study of Animal Exploration. In: Exploration in Animals and Humans. John Archer and Lynda I. A. Birke (eds). Van Nostrand Reinhold (UK) Co. Ltd.

30. P. E. Cowan. 1983. Exploration in Small Mammals: Ethology and Ecology. In: Exploration in Animals and Humans. John Archer and Lynda I. A. Birke (eds). Van Nostrand Reinhold (UK) Co. Ltd.

Chapter 2

Search & Exploration: Definitions and Models

The purpose of the models and their simulation is to build an abstraction with which to think about various characteristics of investigatory behaviors and their relevance to an animal's terrain traversal capabilities. This goal influences our view of investigatory behaviors and we therefore have not attempted to derive universal models and definitions. Instead we have formulated definitions based on: a) previous work with man and other animals, b) the theoretical research conducted in our laboratory on robotic vehicles and, c) the results of empirical work on the locomotion of ungulates over rough terrain. From these we have garnered those elements which appear to be relevant to terrain traversal.

We define search as a behavior which serves to locate in the external, physical environment (as opposed to a search of internal information such as a map) an object of interest whose position in space and time is not known. Exploration is a behavior which serves to collect information about the environment for the purpose of building and maintaining a worl model or map. Locomotor ability is necessary for the execution of most search and exploration endeavors, resulting in a significant interdependence between investigatory behaviors and locomotion itself[31].

In our attempt to model search and exploration, we have relied upon an approach used by cognitive psychologists is studying human decision making[32]. This form of model consists of information flow, information processing, and production of the resultant behavior. Our work in the area of terrain locomotion has shown us that the ability to gather information about a dynamic environment is key to success. Search and exploration are two behaviors in which

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31. Eleanor J. Gibson. 1988. Exploratory Behavior in the Development of Perceiving, Acting, and the Acquiring of Knowledge. Annual Review of Psychology. 39:1-41.

32. Anderson, J. R. 1983. The Architecture of Cognition. Harvard University Press.

collection of information plays a primary role. This makes the information processing approach to modelling search and exploration quite natural.

2.0.1 Search Model

2.0.1.1 Assumptions and Definitions

Our model of search behavior is characterized by the following structure:

- Information
    * Existing object and environmental information ---> search image or template.
    * Sensory information acquired during search ---> guide search.
- Information Processing
    * Incoming sensory information compared with search image.
    * Appropriate movement patterns generated.
- Resultant Behavior
    * Search Begins
    * Interim Movement of Sensors and Body
    * Search Ends

We assume that search behavior begins with an internal motivation to locate a particular object. The priority of the search is relative to other system needs and motivations. The search will continue until either the spatio/temporal location of the object is known or another

motivation becomes dominant. During the search, movement patterns are generated to guide sensors and the body in acquiring information to compare with a search template.

A template is formed using information regarding the search object and the expected environmental context. The template is a representation of the object to be used as a mask in testing the sensed environment. Environmental information allows the template to be tailored to the particular setting. The object and context are necessarily independent. The same object must be able to be identified in a variety of settings, even when located "out-of-context". This template may be multi-sensory. The degree of match between the template and a sensed object may range from complete to none. Rules for acceptance and rejection of the result of a comparison are necessary.

Movement patterns are generated to guide the search. These patterns guide both global and local movements made by the system and its sensors. The two major categories of patterns are random and systematic. The choice of patterns is dependent upon the nature of the object, the environment to be traveled, and the priority of the search.

2.0.1.2 Search Operation

The basic sequence of events which occurs in this model is as follows:

- Begin search

    * Form search template.

    * Select movement pattern strategy which best reflects the nature of the object being sought (for example, random for moving objects, systematic for stationary ones).

- Sense

    * Move sensors to survey immediate area

    * Use environmental context information to choose a likely location to search.

- Compare sensory information with internal template and assess result of comparison.

    * If object found ---> discontinue search.

    * If possible object found ---> investigate more closely.

- End search when object is found or alternative motivation dominates.

2.0.2 Exploratory Behavior

2.0.2.1 Assumptions and Definitions

The basic structure of the exploration model is as shown below:

- Information

    * Existing cognitive map of environment, as gained by prior exploration.

    * Sensory information regarding objects and environment, attention triggered by novelty.

- Information Processing

    * Novelty in sensory information is detected.

    * Maps are spatial scaled.

    * Appropriate movement patterns generated.

- Resultant Behavior

    * Onset of internally driven exploration, patrolling.

* Onset of externally driven exploration, preferential selection of novel stimuli.

* Interim movement of sensors and body.

* Exploration ends.

It appears that exploration can be initiated by either internal or external motivating factors. An internal motivator, for instance, might be the drive to patrol a home range. External motivation would arise through encountering a novel stimulus in the environment. As in search behavior, the priority of this task remains relative to the priorities of other system needs. During exploration, movement patterns are generated to guide collection of information to compare against current spatial/temporal maps.

The system will move about and sample the environment until a difference is detected between that which is expected and that which is encountered. When extreme novelty is found, the response will be to avoid the area. Less extreme novelty will be investigated by alteration of the movement patterns. When important differences are detected, particularly those that represent relatively permanent changes in the environment, they are recorded onto a map representing the area.

2.0.2.2 Exploration Operation

The basic sequence of events occurring during exploration is as described below:

- Begin exploration by either

    * Responding to internal motivations or

    * Responding to external, novel stimuli.

- Sense

    * Select movement pattern which maximizes information collection.

    * Move sensors to survey immediate area.

- Compare sensory information with expected information as held in cognitive maps.

    * Respond to novelty with further investigation of area of interest.

    * Record new information into cognitive maps.

- End exploration when spatial region has been covered or alternative motivation dominates.

Chapter 3

Simulation

3.1 A Computational Model of Searching Behavior

To the walking animal, footholds are a resource in nature whose existence permit it to move about and whose lack present obstacles to progress. This is, of course, a simplification; many legged animals can abandon walking temporarily and for example, jump from one place to another. However, generally speaking, the most immediate problem a walking animal must face is finding the next foothold, typically in some preferred direction. To do this a legged animal has to first locate potential footholds within the nearby region of space and subsequently select suitable footholds within the reach of its legs. From the definition of searching, above, this can be classified as a search for an object whose characteristics are known, a suitable foothold, but whose location is uncertain. Behavior during the process of traversing non-trivial terrain includes a continual resolution or reduction of this uncertainty. The CSAN (Computer Simulation of Animal Navigation) software system is designed to provide a framework for investigating search and exploration behaviors as methods for enhancing the traversal of complex terrain. The simulation is capable of operating with and without prior knowledge of the terrain and has been executed against digital databases taken from real terrain. Its structure and operation is described more fully in Franklin & Taylor (1988).

Using a bimodal perceptual template the CSAN model applies a systematic search process to a simulated surround to locate footholds. Both vision and touch are simulated. Distant vision determines those elements of the terrain, in the current direction of travel, which will be within the reach of the leg. Each of these reachable terrain elements is then scaled up by a factor of four and near vision is applied to determine the elements which have suitable surface properties. Of that set which can be reached and whose surface properties are acceptable, each is tested by placing the tip of the leg on the terrain cell and applying pressure. This tactile test is the final determinant of suitability for a foothold. Footholds are tested in order ranked by their

proximity to the direction indicated by the suggested route computed by the routing engine and the first one to pass all three perceptual criteria is taken. If no footholds are available within the reach of a leg, a further set of rules involving systematic body motion are applied and the body's spatial location and direction of travel are altered to find a suitable foothold or set of footholds. Figures 1a & 1b illustrate the simulation graphic display in which the application of the perceptual model to terrain is shown on the top and the resultant footholds selected are displayed on the bottom, superimposed on the elevation data.

Repeated application of this process of finding and selecting footholds results in a path or trail. If there is no prior knowledge of the ground available, then the animal's behavior is considered trail blazing. Trail blazing in which some information is retained regarding the terrain and its traversal is, by the definition above, exploration. Thus the two activities may occur and probably do commonly occur concurrently.

The simulation provides a testbed for trail blazing search heuristics. It has been exercised with both synthetic terrain made from fractal algorithms and on an elevation map of the eastern foothills of the Rocky Mts. just southwest of Denver. Both terrains are illustrated in Figure 2, a photograph from a computer graphic display. In both cases the terrain was successfully traversed in a number of different regions.

In trail following behavior terrain route and path selection computational subsystems operate together to result in the actual path taken. Their interrelationships are illustrated in Figure 3 along with their logical relationship to the perception subsystem. Route considerations, based on periodic cost or utility analyses of prior terrain knowledge, determine where to make initial attempts to locate footholds. However, some searching also occurs even when prior information is available. Although route information dictates the direction in which an initial attempt is made to find a path, lack of suitable footing should and does result in searching. Since the route knowledge-base, the cognitive maps, do not retain information for a long period of time at a level of spatial detail sufficient to recall every foothold in a trail previously explored, some searching is an inevitable part of trail following behavior.

The primary value of this simulation, to date, is that:

- it has incorporated a diverse set of rules, sensing modalities and kinds of information into one working whole;

- it has been possible to generate search behavior on synthetic and real terrains of high complexity;

- these searches have resulted in successful traversal of these experimental terrains by trail blazing, a behavior which results from the model interacting with environmental conditions of high uncertainty.

- when accurate prior information is available, the simulation exhibits trail following behavior, with search relegated to the most local details of foot placement.

Successful traversal of complex terrain with no or limited prior knowledge argues that the components of the model are sufficient for trail blazing behavior. Further, the model suggests that trail blazing and trail following are not mutually exclusive behaviors but are a matter of degree related to the level of detailed knowledge about the terrain. Thus the model contains the necessary information and processing to make use of whatever level of detail is available regarding the terrain for its traversal. Further empirical work with selected species will enrich this logical framework by providing more heuristics for search and exploration of terrain.I

3.2 Blazing and Following Trails

Our primary goal in developing a simulation of trail blazing and following was to illustrate a major benefit of investigatory behavior. We wished to show how costs of performing such behaviors could be outweighed by the benefit of having gathered information about resources available in the environment. Theoretically the gathered information could be used to expedite location of resources at times in the future when lengthy searches would incur significant costs, potentially far in excess of the initial investment in investigatory behavior. Cowan[33] cites a number of empirical studies which indicate that small mammals are in fact better able to avoid predation if they have been given the opportunity to explore a new environment before the introduction of predators.

We chose a context for this simulation that would be directly applicable to locomotion activities: trail finding and following. This context was chosen because of the commonality of such activities in the natural world and due to the usefulness of these activities to the success of terrain traversal in particular[34]. Chattergy, in his research on heuristics for navigation of a

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33. P. E. Cowan. 1983. Exploration in Small Mammals: Ethology and Ecology. In: Exploration in Animals and Humans. John Archer and Lynda I. A. Birke (eds). Van Nostrand Reinhold (UK) Co. Ltd.

34. Gibson, J.J. 1958. Visually controlled locomotion and visual orientation in animals. Brit. J. Psychol. 49:182-194.

mobile robot [35], has also identified path finding and path following as two important aspects of autonomous machine navigation.

The development proceeded through augmentation of an existing simulation of autonomous vehicle terrain traversal with concepts taken from the investigatory behaviors of animals[36]. The given simulation provided us with an autonomous route planning system which could serve as a basis for our implementation. In this system, simulated vehicles traverse a complex spatial environment represented by a fractal image. Figure 4 shows the general simulation display. Each vehicle has a spatial memory and a simulated sensor which operate to provide the vehicle with information regarding its surroundings. A routing engine in this simulation determines the least-cost path from a starting point to a destination point in the fractal world, where each pixel has a given traversability ground-cost associated with it.

In the initial phase of the implementation, each vehicle was endowed with search and exploration capabilities in order to identify its own network of trails within a fractal world (Figure 5.) and to retain this information in a trail map. Algorithms were used to guide vehicle movement and sensing while searching for terrain which would meet the established requirements for trail designation. The vehicle moved in a straight line as far as possible and when necessary turned at a random angle. The requirements set for trail terrain served in essence as a search image. Trail terrain had to be less than a given cost value and continuous with existing trail. As trail terrain was identified it was marked as such in a trail map. Once established, a trail system could then be used by the vehicle for navigating between two points located on the trails (Figure 6.). The trail system would not always provide the least-cost path to a goal, but would always allow a proven path to be located quickly. This was implemented by masking all non-trail pixels with a very high cost value in the terrain at the time of routing between trail points. Though this may seem artificial, we hypothesize that this is analogous to what natural systems accomplish. In nature, it appears that established trails are given clear preference over untried terrain. Utilizing trails reduces the problem of terrain traversal almost to one of knowing where to get on the trail and where to get off. Between trail start and destination points the effort is reduced from finding specific footholds to monitoring terrain against expected conditions. The role of vision and touch appear to change significantly between trail finding and trail following.

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35. Chattergy, R. 1985. Some Heuristics ' the Navigation of a Robot. International Journal of Robotics Research. Vol 4. No 1.

36. Quek, F.K.H., Franklin, R., Pont, W.F. A decision system for autonomous robot navigation over rough terrain. September 1985. Proc. SPIE Conf. on Intelligent Robots and Computer Vision, V. 579 #59-50, pp. 377-388. Boston.

A second phase of development extended the capabilities to allow vehicles to navigate to points off the trail system as well as on. To reach a point off-trail, a vehicle follows trails as far as possible and then completes travel to the goal by using the existing, slower, routing engine methods of the original navigation simulation as described above (Figure 7.).

The results of the simulation were as expected. Time was given to establish an adequate trail system. We typically let this process run for 30 to 60 minutes. Whereas planning and traversing a route between two points using the previous system required on the order of minutes to perform, once a trail system was established movement between points on the trail could take place almost instantaneously. Of course, this change is dependent upon our ability to re-program the mechanics of the simulation, but we feel it does provide an illustration of the type of simplification which may be taking place in natural systems. Exploratory behavior serves to significantly narrow the gap between planned routes and planned paths.

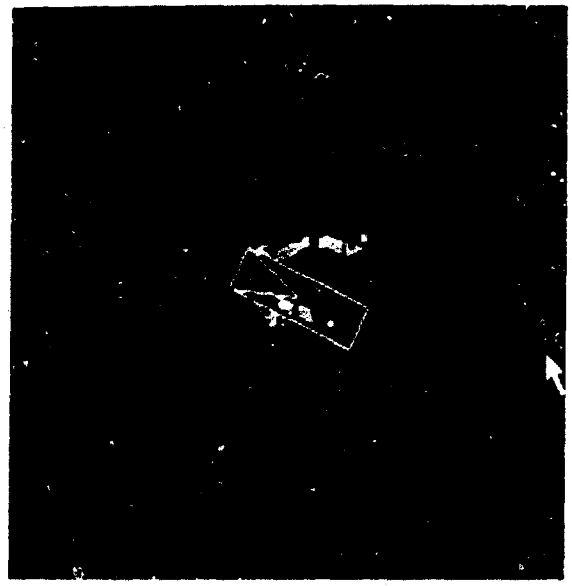

Figure 1a. A detail from the graphic display of the CSAN system shows the model animal represented as a rectangle with the left front leg visible. The dark red regions represent the sequence of visual scan information stored in the working memory. Within this working memory, the perceptual criteria for suitable footholds are applied: blue represents current and immediately past reachable leg volumes, white indicates the regions within the blue where surface characteristics were acceptable, yellow indicates footholds tested by applying force to the area and found acceptable to the tactile criterion. The small orange regions indicate potential footholds which, upon the application of force, failed the tactile criterion.

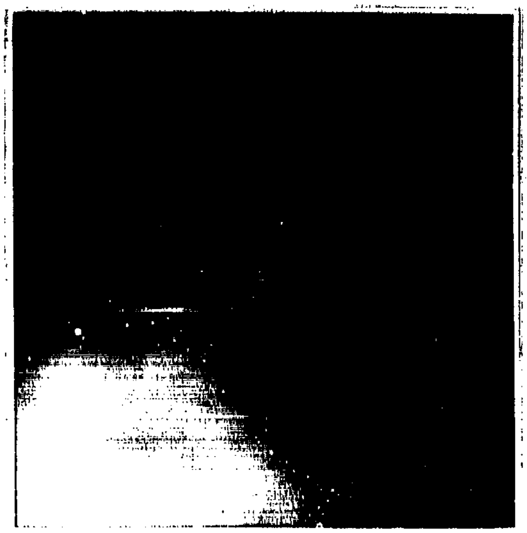

Figure 1b. The locations of footholds acceptable to vision and those which passed and failed the tactile criterion are superimposed on a display of terrain elevation. The higher altitudes are indicated by lighter grey values in this top-down display.

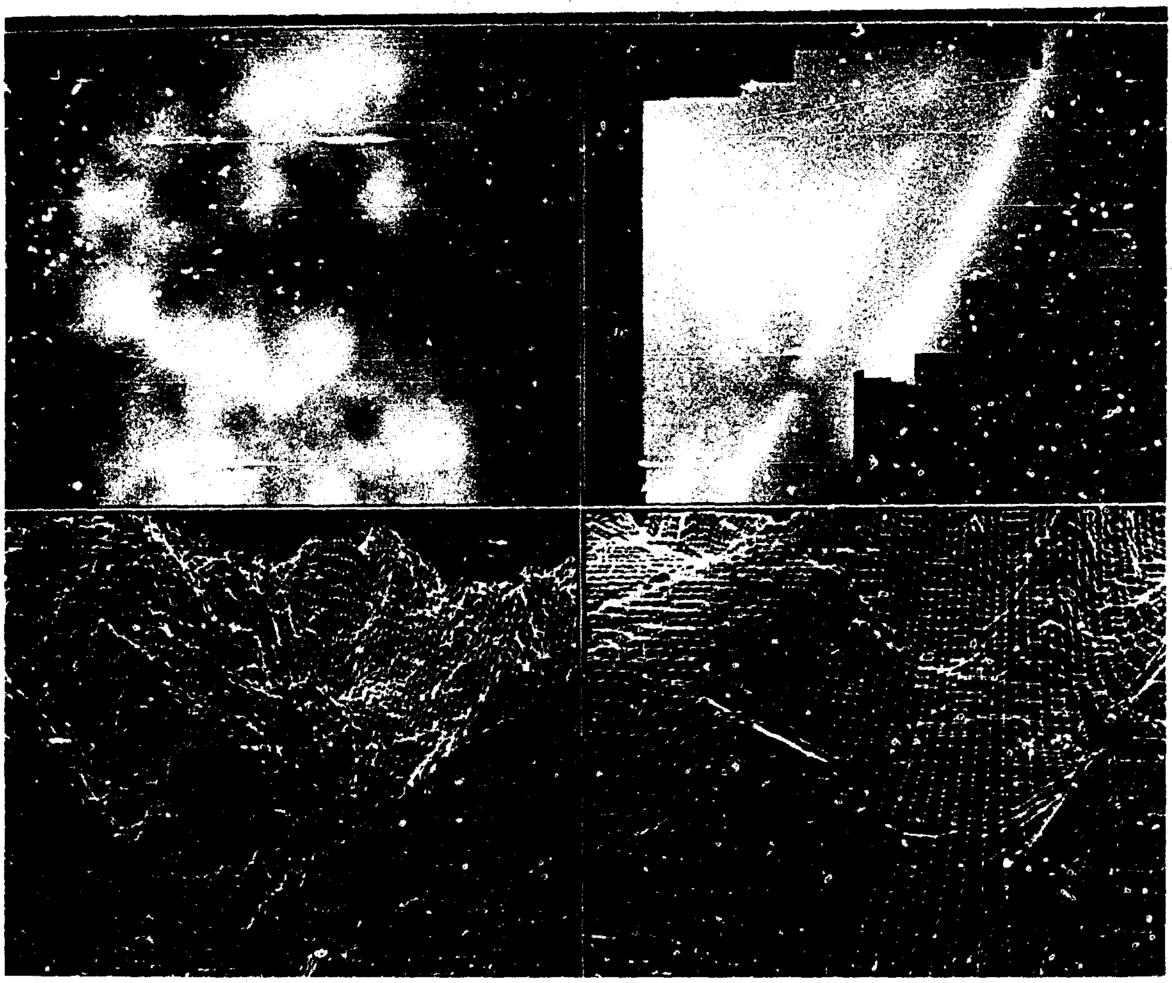

Figure 2. The CSAN simulation has been exercised on synthetic (left) and real (right) terrain. The synthetic terrain is shown at a resolution of 1 foot per element and was constructed using a fractal carpet superimposed on regular geometeric shapes. The real terrain has a 5 meter resolution. It was derived from an Engineering Topographic Laboratory elevation map of a region in eastern foothills of the Rocky Mts.

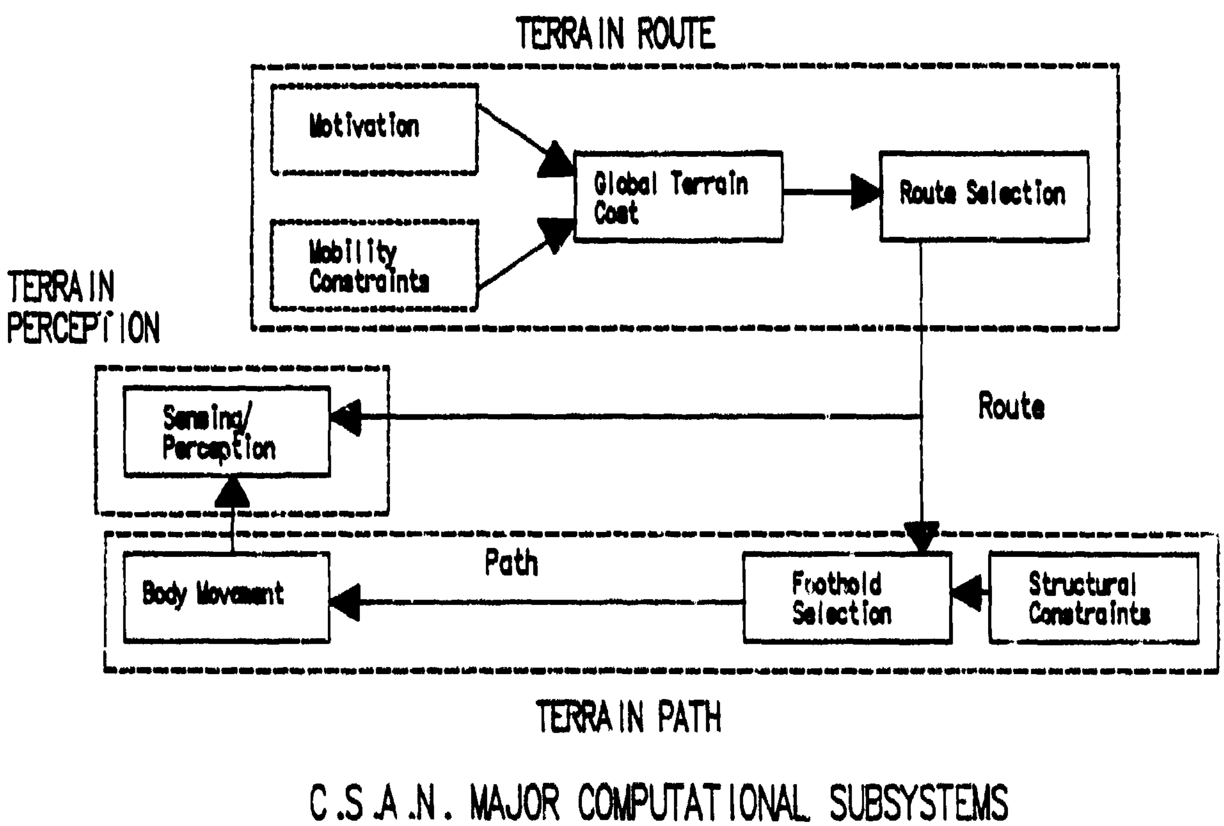

Figure 3. A schematic illustration of the three computational subsystems of CSAN is shown. The routing subsystem produces a list of points which represent the best estimate of a route, based on prior information. The path subsystem finds footholds, attempting to stay as close as possible to the route. The perception subsystem interprets terrain to find suitable footholds.

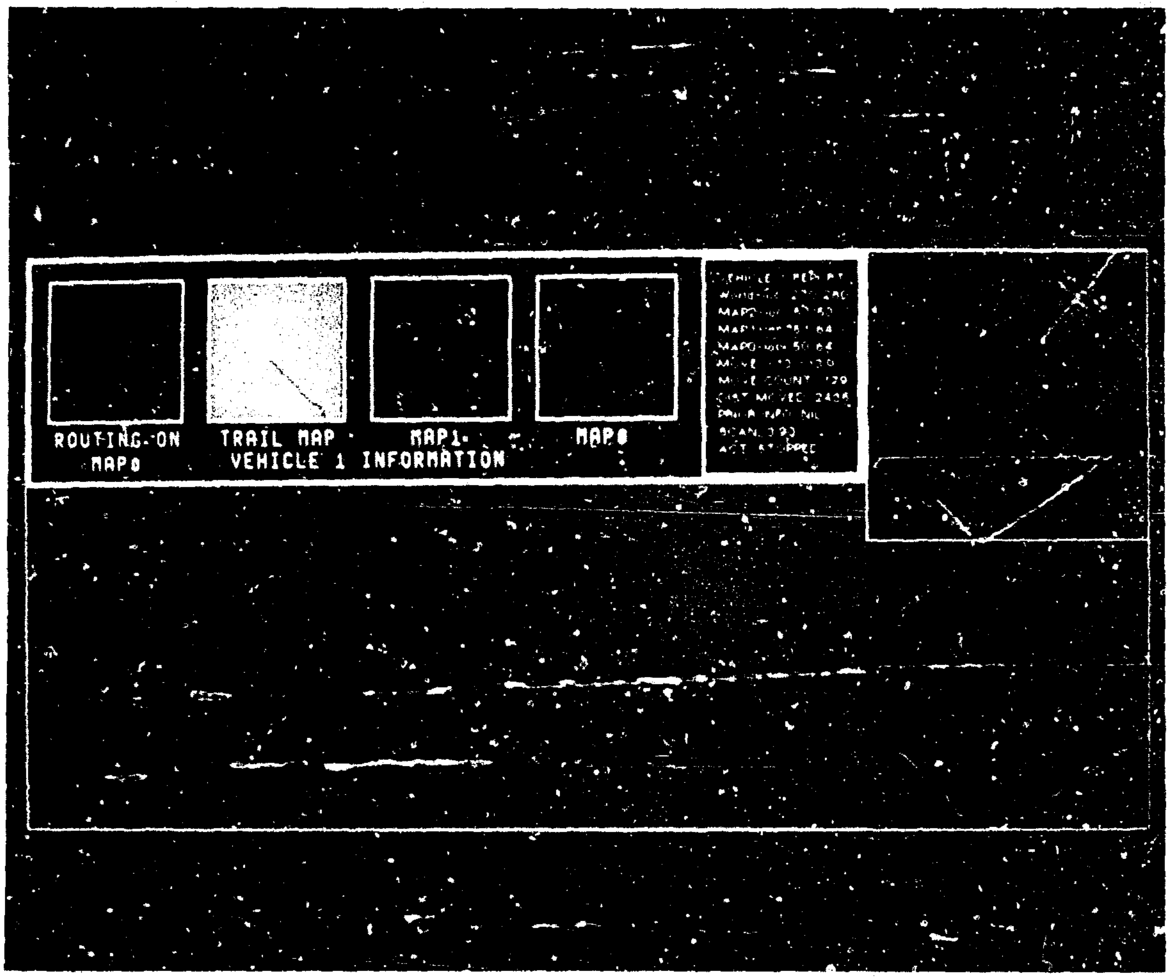

Figure 4. In the Trail Finding and Following Simulation search and exploration behaviors were implemented in order to develop a set of trails in a fractal terrain (top right) and record the trail information into a trail map (top, second from left).

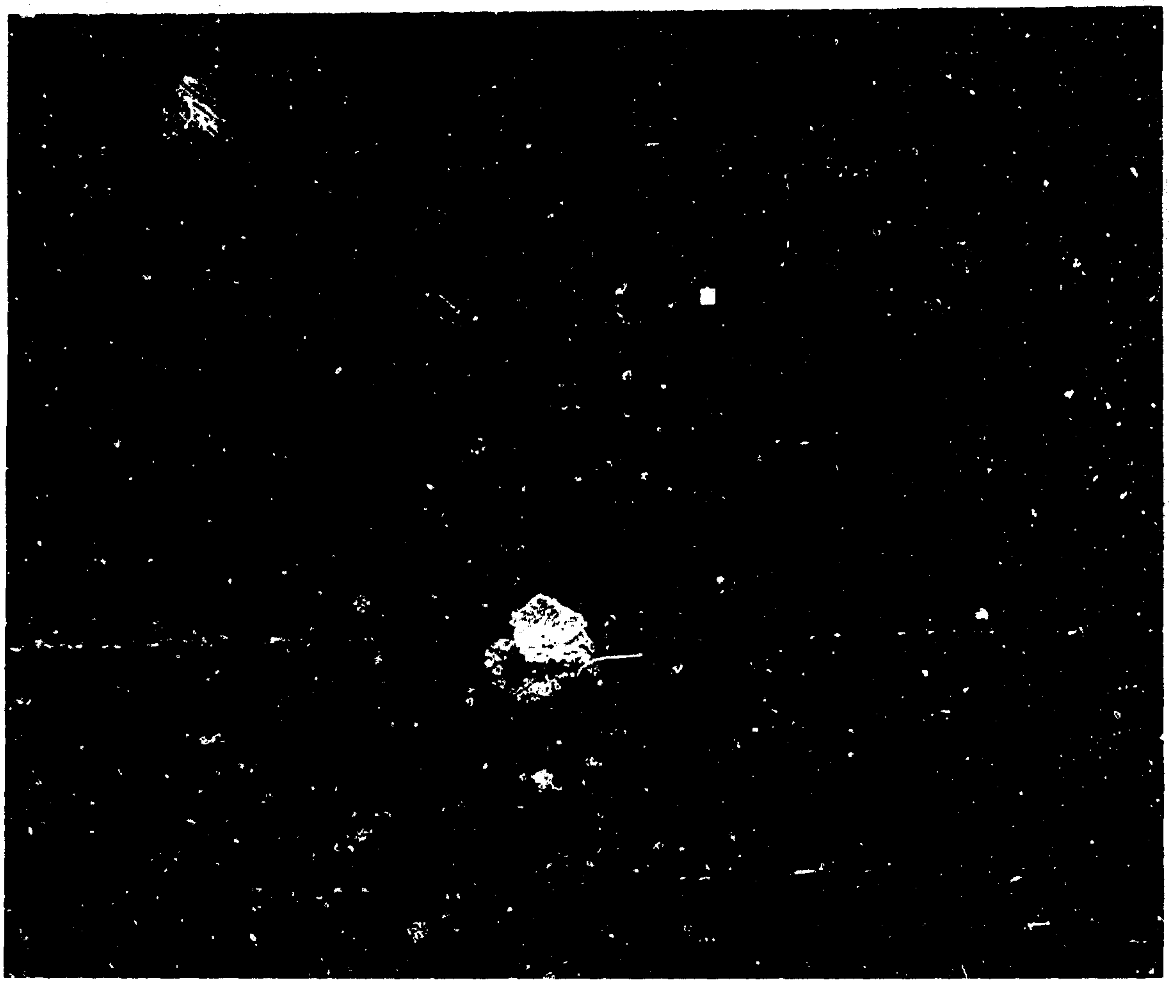

Figure 5. Movement in the Trail Finding and Following Simulation proceeds as far as possible in a straight line and then turns at a random angle when necessary to continue the trail. Trail segments are required to be low cost and contiguous with existing trail. An established trail network is shown here in yellow.

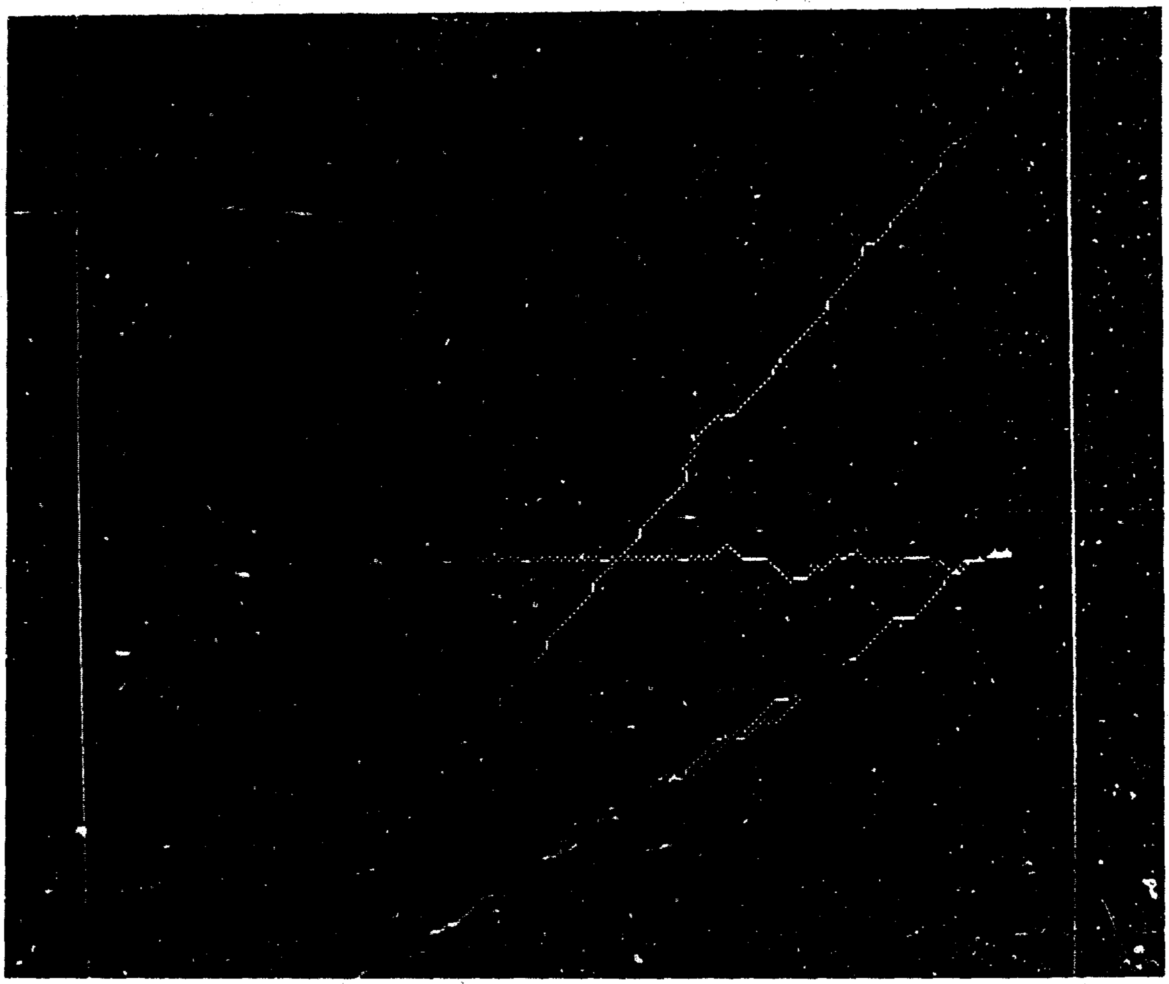

Figure 6. Once a trail system is established, navigation between points on the trails can be accomplished rapidly. Shown here, navigation has taken place from the end of the trail network to the position marked by the red square.

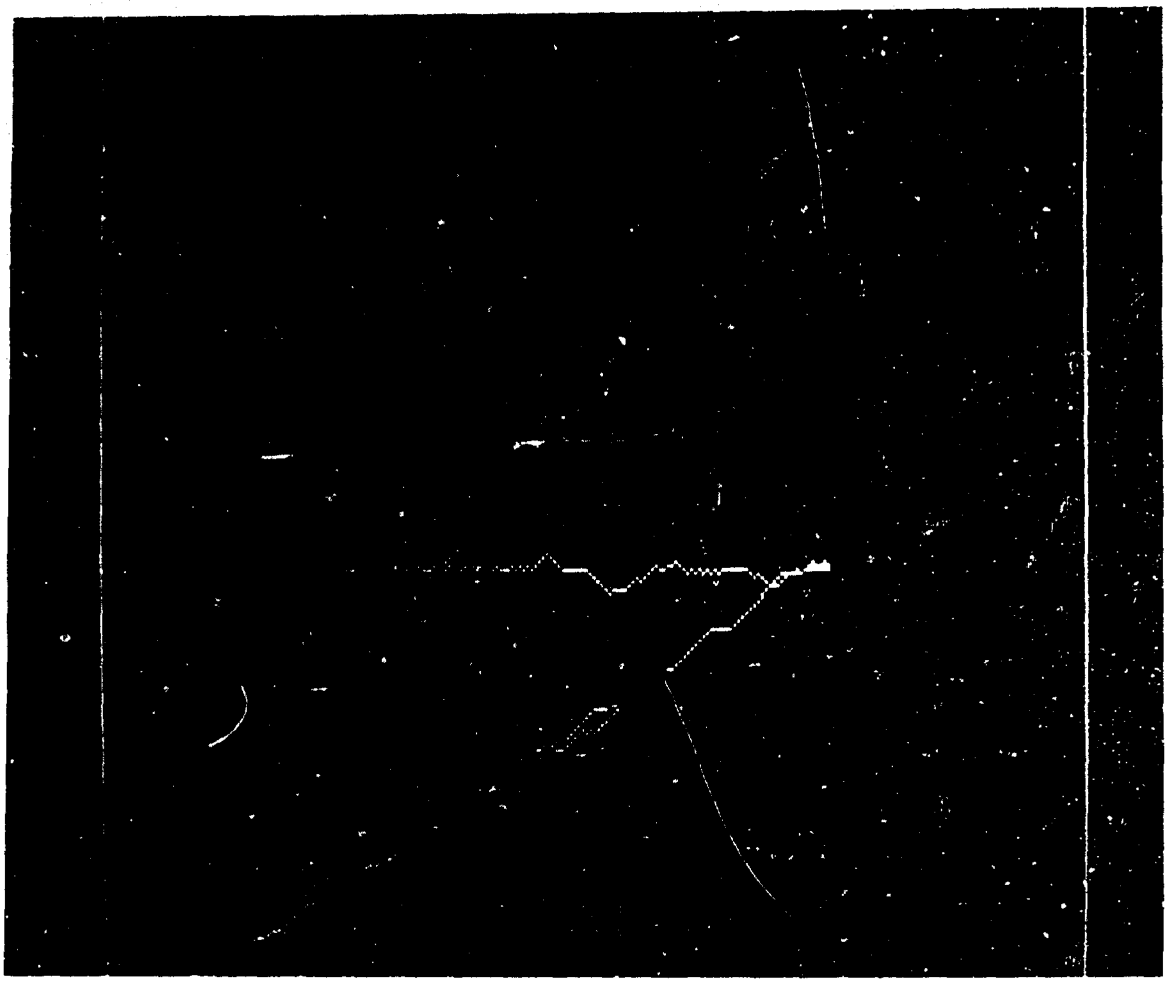

Figure 7. In the Trail Finding and Trail Following Simulation, navigation can also take place from points on the trail systems to points off trail, as shown here. Trail is utilized for as much of the traversal as possible and then navigation proceeds off-trail.